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INSIDE

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

REVERSE POLARISATION

Switching to a *p*-down architecture produces a near-theoretical operating voltage for the green LED

CRYSTAL CLEAR OBJECTIVES

Streamlined manufacturing and expanding into new materials are the two key elements in IQE's growth strategy

CRANKING UP THE VOLTAGE

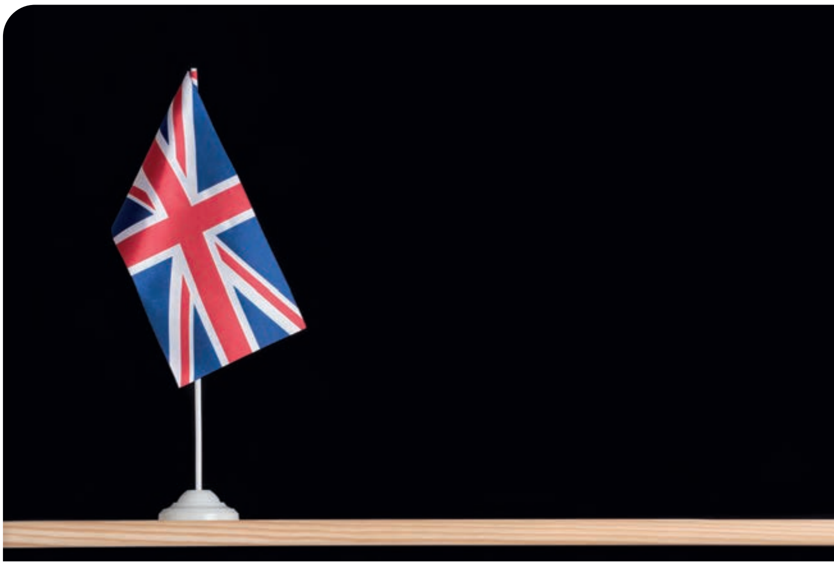
GaN HEMTs with minimal output capacitance and terminated harmonics deliver record-breaking powers and efficiencies


AIXTRON
AIXTRON

VIEWPOINT

By Dr Richard Stevenson, Editor

Strong leadership



OVER the last few months my country, the UK, has become the laughing stock of the world. Despite a parliamentary democracy dating back nearly 200 years, we are going through outrageously turbulent times, epitomised by our former Prime Minister, Liz Truss, resigning after just 45 days.

The undoing of Truss does not stem from her view of what must be fixed in the UK. She's right that productivity is a problem that has held the country back for decades. Even her solution, a form of trickledown economics that shifts money towards the wealthy, in the belief that this will ultimately raise prosperity for all, was not her downfall. While it may have been unpopular and it's not got my support, one can make a case for this. What's made her position untenable is a complete disregard for any rigour, emphasised by deciding to sidestep the scrutiny of the Office for Budget Responsibility.

Fortunately, not everyone with a leadership role in the UK is as reckless as our former PM. Those that are far more astute include the new CEO of IQE, Americo Lemos. Recently I interviewed him – to hear his views, turn to page 26 of this issue.

I'm a firm believer in the value of experience, which provides the foundation for making good decisions. Lemos has this attribute in spades, with knowledge that extends from products to chips and foundries, and roles that have led him to spend time in Europe, the UK and Asia.

Lemos will have drawn on this background when creating his strategy to take IQE to new highs. A key element within his plan is to optimise the footprint of this multinational. In practice, this means having just one site in Asia, in Taiwan; consolidating the sites in the US from three to two; and moving some of the capacity from the headquarters, on the outskirts of Cardiff, to the company's far larger facility at nearby Newport. R&D is to be retained at its smaller UK facility. With this move IQE will be better positioned to offer customers the opportunity to scale with a company that has a global footprint and industry-leading technology.

Like any leader, how the future unfolds will involve the interplay of the quality of the decision-making, its implementation, and factors far beyond the company's control. Right now, geo-political considerations are playing into the hands of IQE, with its sites on three continents; while the softness in the smartphone market is providing a gentle headwind to sales of RF and VCSEL epiwafers.

I finished my interview by asking Lemos if shareholders can start to expect any dividends – this is not the norm for IQE. He did not evade this question, tackling it head on, arguing that money is needed to invest in the growth of this company. I like this guy: he's a leader, not a politician.

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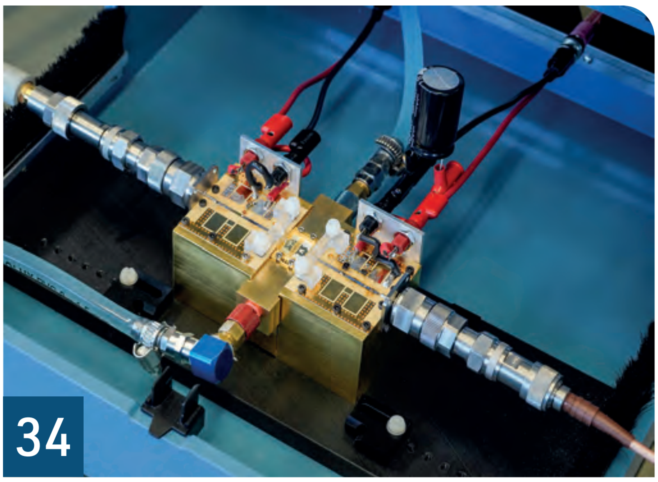

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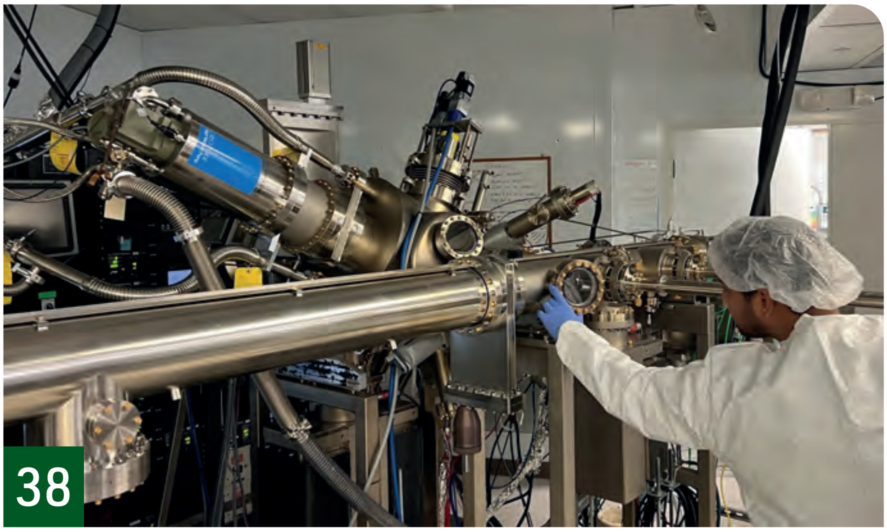

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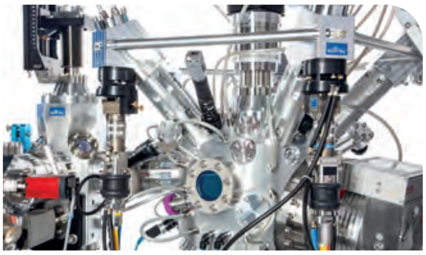

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Kyocera develops novel GaN laser chip

Company unveils new process to create functioning 100 micron length micro-light sources

KYOCERA has developed a new thin-film process technology for making unique silicon substrates for GaN-based micro-light sources, including short-cavity lasers and microLEDs. Because these sources offer higher definition, smaller size, and lighter weight, they are considered essential to next-generation automotive displays, wearable smart glasses, communication equipment, and medical devices.

GaN-based light-source devices, both microLEDs and lasers, have typically been fabricated on sapphire and GaN substrates. Conventional processes involve forming a thin GaN device layer for the light source directly onto the sapphire substrate by heating it to a high temperature in a controlled gas atmosphere. The device layer has to then be removed, or 'peeled' from the substrate, to create a GaN-based micro-light-source. Despite rising demand for smaller devices, however, three separate challenges threaten the ability of this process to achieve miniaturization targets in the near future.

In case of microLEDs, current processes require difficult steps to divide the device layer into individual light sources on the substrate; and then, to separate the device layer from the substrate. As devices become smaller, the technical challenge of this peeling process can result in an unacceptably low yield.

Fabrication of micro-light sources is also problematic because device layers must be deposited onto sapphire, silicon, or other materials with crystal structures that differ from that of the device layer. This creates high defect density and inherent quality control challenges.

Kyocera successfully developed the new process technology at the company's Research Institute for Advanced Materials and Devices in Kyoto, Japan. First, its grows a GaN layer on silicon substrate which is available in high volumes at a low cost. The GaN layer is then masked with a non-growing material that features an opening in the center. After this, when a GaN layer is formed on the silicon substrate, GaN nuclei grow over the opening in the mask. The GaN layer, which is a growing nucleus, has many defects at the initial stage of growth; but, by forming the GaN layer laterally, high-quality GaN layers with a low defect density can be created, and devices can be fabricated successfully from this low-defect region of the GaN layer.

Masking the GaN layer with a material that does not grow suppresses bonding between the silcion substrate and the GaN layer, greatly simplifying the peeling process. Since Kyocera's process can deposit low-defect GaN over a wider area than before, consistent fabrication of high-quality device layers is possible. Kyocera says its new method facilitates successful and reliable separation of the GaN device layer from the relatively inexpensive silicon substrate, which will greatly reduce manufacturing costs.

Qorvo and SK Siltron CSS sign SiC deal

US-BASED Qorvo and SK Siltron CSS, a Korean semiconductor wafer manufacturer, have finalised a multi-year supply agreement for SiC bare and epitaxial wafers. This agreement will promote US domestic semiconductor supply chain resilience and a greater ability to support the rapidly rising demand for advanced SiC solutions, specifically in the automotive market. This agreement will also provide end-user customers a level of protection and confidence as customers adopt Qorvo's Gen 4 SiC FET solutions.

SK Siltron CSS is a subsidiary of South Korea based SK Siltron, a part of the SK Group.

BluGlass partners with Ganvix on green VCSELs

Ganvix has selected BluGlass' RPCVD technology to enable the development of green VCSELs for advanced applications

BLUGLASS has entered into a collaboration with Ganvix to develop cutting-edge GaN VCSELs for green wavelengths. Ganvix is a developer of nanoporous GaN VCSELs, a type of laser diode.

Under the paid development agreement, BluGlass will provide Ganvix with green quantum-well epitaxy services using its proprietary remote-plasma chemical vapour deposition (RPCVD) technology. BluGlass' technology offers key performance advantages for green wavelengths, to enable higher power, brighter green performance. RPCVD complements Ganvix's DBR technology for GaN VCSELs.

Green GaN VCSELs have broad market applications including consumer electronics, industrial, medical, life sciences and light engines for laser scanning displays.

Jim Haden, BluGlass president, said: "The advantages of BluGlass' low-temperature RPCVD technology provides significant commercial benefits for longer-wavelength lasers, including green. Our unique low-temperature, low-hydrogen growth technology enables brighter, higher performing green quantum-wells – the key light emitting region in lasers."

Haden added: "Our collaboration with Ganvix will advance our RPCVD roadmaps and expands our market opportunity. Importantly, the collaboration complements our own product and commercialisation roadmap, which is focused on edge-emitting laser diodes."

Ganvix CEO, John Fijol, remarked: "This significant collaboration to combine nanoporous VCSEL architecture with BluGlass' unique RPCVD technology

provides a path to bring green GaN VCSELs to market. There are many high-growth markets for this exciting technology, including advanced applications such as augmented and virtual reality headsets, pico projectors, and 5G wireless communications."

During initial development BluGlass will receive payment for services, which the company does not consider material. On successful commercialisation, BluGlass expects to receive material revenues from ongoing orders.

MICLEDI announces red GaN microLEDs

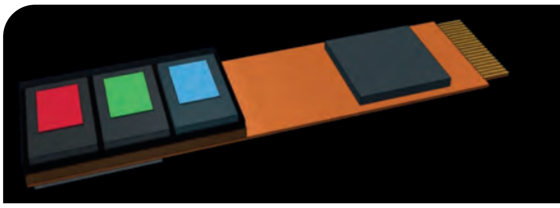
MICLEDI MICRODISPLAYS, a developer of microLED displays for augmented reality (AR) glasses, has demonstrated 630 nm wavelength red GaN with full-width-half-max (FWHM) in the range of 50 nm.

Historically, red microLEDs have suffered a reputation as a poor performing part – this breakthrough by Micledi helps to put that reputation to rest. Red GaN is compatible with Micledi's proprietary CMOS-fab technology and follows the identical process recipe of the company's blue and green arrays for consistency.

It accommodates pixel-level micro lenses for high-efficiency optics integration and is tailored for industry-standard 300 mm commercial foundries for high-volume mass production.

Sean Lord, CEO, said: "AR headgear in the market today ranges from monochrome monocles for limited information-only displays to monochrome headsets and heads-up displays to full-colour glasses for industrial, enterprise and military applications. Prices range from $1000 to over $5000 per headset, which is too high for the average consumer. With the addition of red GaN to our tool kit, Micledi is perfectly positioned to bring the cost and volume advantages of its 300 mm manufacturing flow to open the door to future generations of AR glasses that consumers can afford and enjoy."

With this announcement, Micledi now has all three microLED colours coming into the market. The company continues its close affiliation with imec and other significant partners.



"Red GaN is but one option," added Lord. "Alternative approaches vary from AlInGaP to quantum dot, and other techniques. Micledi is committed to pushing the cost, reliability, and performance envelope of each of these alternatives to provide the best in full-colour microLED display modules across a broad range of performance parameters for transparent lens AR glasses."

Micledi introduced its blue GaN and green GaN LED display test chips earlier this year. The new red samples are projected to be available to customers before the end of the year.

Rohm, Mazda, and Imasen sign SiC e-Axle deal

Through the collaboration, Rohm will further develop SiC MOSFETs and modules by working backwards from the finished vehicle

ROHM has signed a joint development agreement with Mazda Motor Corporation and Imasen Electric Industrial for inverters and SiC power modules to be used in the electric drive units of electric vehicles, including e-Axle.

As the 'heart of the EV', e-Axle integrates a motor, reduction gearbox and inverter into a single unit that plays a large part in determining the driving performance and power-conversion efficiency of electric vehicles. SiC MOSFETs in particular are expected to improve efficiency even further.

Rohm will carry out joint inverter development for e-Axle by participating in a 'cooperative framework for the electric drive units development and production' with companies such as Imasen and led by Mazda. At the same time, Rohm will contribute to the creation of industry-leading compact, high efficiency electrical units by developing and supplying advanced SiC power modules that provide improved performance.

Through this collaboration, Rohm will develop even more competitive SiC MOSFETs and modules by working backwards from the finished vehicle to understand the performance and optimal drive method required for power semiconductors.

Besides creating new value through mutual understanding between car and device manufacturers, the three companies also support technical innovation in the automotive field and contribute to a sustainable society by leveraging extensive knowledge, technologies, and products garnered on a global basis.

Ichiro Hirose, director and senior managing executive officer; Oversight of R&D, Cost Innovation and Innovation, Mazda Motor Corporation said: "We are pleased to collaborate on the development and production of e-Axle with Rohm, who hopes to create a sustainable mobility society through outstanding semiconductor technologies and advanced system solution development capabilities, to co-create a new value chain that directly links semiconductor devices and vehicles in both directions as electrification brings us closer to carbon neutrality."

"By partnering with like-minded companies, Mazda is committed to injecting 'driving pleasure' into every product – including electric vehicles."

Katsumi Azuma, director and senior managing executive officer and COO, Rohm, added: "We are extremely pleased to work together on the development and production of e-Axle with Mazda, who is committed to providing 'driving pleasure' that expresses the inherent appeal of cars."

"Through this partnership, we hope that by reflecting the true demands and requests in our products we can develop automotive systems that contribute to decarbonization while allowing us to gain a deeper understanding of Mazda's goal of creating cars that are sustainable with the earth and society."

Azuma continued: "As the role of semiconductors in the automotive market continues to grow, Rohm will strive to manufacture high quality products and contribute to the creation of a sustainable mobility society by offering a wide range of solutions."

UK orders Nexperia to divest Newport Wafer Fab

UK Government says Chinese firm's ownership is a risk to national security

THE UK GOVERNMENT has made a final order for the Chinese owned chip company Nexperia to sell at least 86 percent of Newport wafer fab (NNL), stating national security concerns.

The review was triggered when on 5 July 2021 Nexperia gained an additional 86 percent of the share capital of Newport Wafer Fab (now NNL), taking its shareholding to 100 percent.

The Secretary of State's order says the ownership is a risk to national security relating to technology and know-how that could result from a potential reintroduction of compound semiconductor activities at the Newport site, and the potential for those activities to undermine the UK's own capabilities.

In addition there are concerns that the location of the site could facilitate access to technological expertise and know-how in the South Wales Compound Semiconductor Cluster, and the links between the site and the Cluster may prevent the Cluster being engaged in future projects relevant to national security.

Nexperia, which is based in the Netherlands but is a subsidiary of Chinese company Wingtech Technology, says it is shocked by the decision and does not accept the potential national security concerns raised.

Responding to the decision on behalf of Nexperia, UK country manager, Toni Versluijs, said: "We are genuinely shocked. The decision is wrong, and we will appeal to overturn this divestment order to protect the over 500 jobs at Newport. This decision sends a clear signal that the UK is closed for business. The UK is not Levelling Up but Levelling Down communities like South Wales."

He added: "We rescued an investment-starved company from collapse. We have repaid taxpayer loans, secured jobs, wages, bonuses and pensions, and agreed to spend more than £80 milion on equipment upgrades since early 2021. Those who sold the business to us agreed that it was the only viable solution, and the deal was publicly welcomed by the Welsh Government."

Simon Thomas, CEO of UK-based Graphene microchip firm, Paragraf commented: "It's good to at last see a decision in the case of Newport Wafer Fab. The industry understands that national security is undoubtedly important, and every care must be taken to ensure that the UK and its interests are protected. Still, significant steps must be taken to minimise the delays involved in these investigations in the future."

He added: "British companies cannot afford to lose competitive advantage, which is the unintended result of these drawn-out investigations and absence of direction that causes customers and shareholders to become frustrated and potentially look for clarity elsewhere."

"The Government should consider concrete and efficient processes to review national security concerns in a manner that provides a timely outcome for all in a clearly outlined and transparent process. Of course, we need to protect national security, but not to the detriment of British businesses."

Infineon and Stellantis sign multi-year SiC deal

INFINEON and the Netherlands-based automotive giant Stellantis have signed a non-binding MoU as a first step towards a potential multi-year supply cooperation for SiC semiconductors. Infineon would reserve manufacturing capacity and supply CoolSiC 'bare die' chips in the second half of the decade to the direct Tier 1 suppliers of Stellantis. The potential sourcing volume and capacity reservation have a value of significantly more than €1 billion.

"We firmly believe in electromobility and are excited to develop partnerships with leading automotive companies like Stellantis that make it a part of people's everyday life," said Peter Schiefer division president Automotive of Infineon. "Compared to traditional power technologies, SiC increases the range, efficiency and performance of electric vehicles. With our leading CoolSiC technology and continuous investments in our manufacturing capacities, we are well positioned to meet the growing demand for power electronics in electromobility."

Infineon and Stellantis are in talks about delivering the CoolSiC Gen2p 1200 V and CoolSiC Gen2p 750 V chips for electric vehicles under Stellantis brands. The performance, reliability, and quality of CoolSiC technology would allow Stellantis to build vehicles with longer ranges and lower consumption for the best user experience – and support the company in its efforts to standardise, simplify and modernise platforms.

Hunan Sanan secures $524 million SiC order

SiC chips will be manufactured in Hunan Sanan's mega fab in Changsha

HUNAN SANAN, a subsidiary of Sanan Optoelectronics, will supply SiC chips to a prominent automaker's new electric vehicle product line in the next few years.

Tony Chiang, general manager of Hunan Sanan, said: "Our agreement with this strategic partner further demonstrates the automotive industry's commitment to providing innovative electrification experience to the market and leveraging the advantages of wide bandgap semiconductors to improve overall vehicle performance."

Chiang added: "The agreement ensures a long-term supply of SiC to our customer to help them realise their promise of low-carbon, smart mobility."

The SiC chips in the agreement will be manufactured in the Hunan Sanan's mega fab in Changsha, said to be the first vertically integrated SiC wafer manufacturing service platform in China, providing an in-house supply chain spanning SiC crystals, substrates, epitaxy, chip manufacturing, packaging and testing, with a committed annual production capacity of 500,000 SiC 6-inch wafers.

Hunan Sanan has recently obtained IATF 16949 system certification while the automotive-grade SiC MOSFETs have been verified with the cooperation of strategic partners, and are expected to be released in production in early 2024.

Sike Semiconductor, a company jointly established by Hunan Sanan and Li Auto, also officially started construction this past August and is expected to start production in 2024, with a planned annual production capacity of 2.4 million half-bridge SiC power modules.

Hunan Sanan's SiC technology will provide energy for the NEV power system for medium- and high-voltage platforms.

$2.4 billion CS substrate market by 2027

Substrate market is growing at 16 percent CAGR, driven by power and photonics applications, says Yole Intelligence

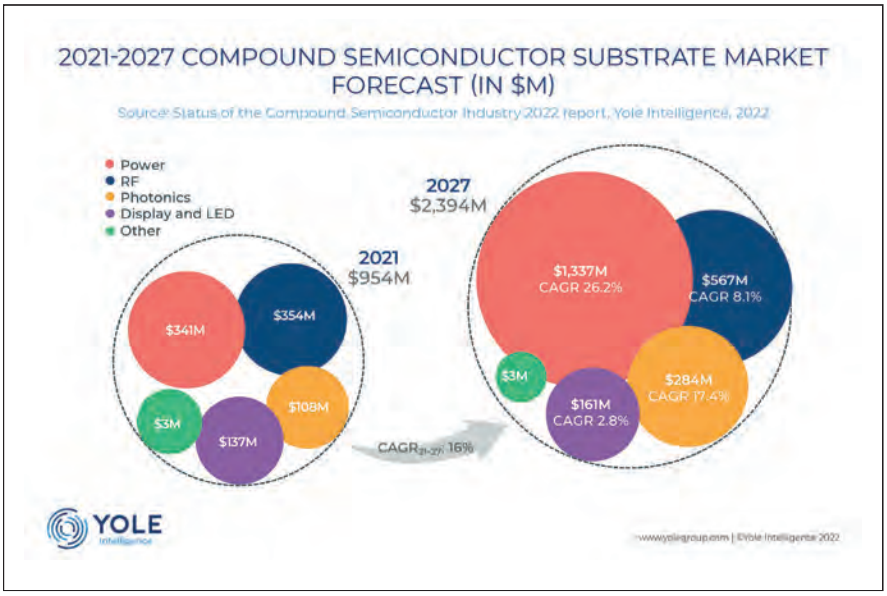
DRIVEN by power and photonics applications, the compound semiconductor substrates market will be worth close to $2.4 billion by 2027, growing at 16 percent CAGR between 2021 and 2027, according to Yole Intelligence's new *Status of Compound Semiconductors Industry 2022* report.

CS has been adopted in many applications over the decades; more recently SiC and GaN in power, GaN and GaAs in RF, GaAs and InP in photonics, and LED and microLED in display, have gained momentum. As a result, the substrate and epiwafer markets are also expected to grow.

Poshun Chiu, senior technology and market analyst specialising in Compound Semiconductors and Emerging Substrates at Yole Intelligence, part of Yole Group said: "Wolfspeed is the leading SiC substrate and epiwafer supplier for power SiC and RF GaN. As the larger-format substrate is the strategic resource in the next generation of device manufacturing, the opening of 8-inch wafer fabs and the expansion of material capacity illustrates the ambitious targets aimed at in the coming decade."

Meanwhile, II-VI closed its acquisition of Coherent and renamed the company, thus illustrating its change of focus. Today, Coherent is the leading photonic device player as well as the leading SiC substrate supplier for power and RF applications. Moreover, it is working with SEDI on RF GaN device manufacturing and has entered the power SiC device business with GE. Both are strengthening their competitiveness from the substrate level to the device level.

> As the demands for 5G connectivity, EVs, and fast chargers for smartphones come to the market, compound semiconductors will grow in both volume and market value



AXT, Sumitomo Electric, Freiberger, and SICC are the leading suppliers of GaAs, InP, and semi-insulating SiC substrates. Their objectives of growing their revenues rely on expanding into other CS materials. Players are looking at the synergy between GaAs and InP substrates for RF, photonic, and microLED applications. Also, players from semi-insulating SiC are entering *n*-type SiC as it is a market with a higher growth rate.

Taha Ayari, technology and market analyst, Compound Semiconductor and Emerging Substrates, at Yole Intelligence said: "Epiwafer suppliers benefit from the different dynamics of the CS open epiwafer market. IQE has been involved in various CS markets (for example, RF GaAs and GaN), as the double-digit CAGRs of InP and GaAs photonics represent markets with both volume and scale. And microLED is a booming market, expected to double every year in the coming five years. VPEC has succeeded in becoming the largest supplier of RF GaAs epiwafers in the open market, and the company continues increasing its engagement in photonics for future growth".

Ezgi Dogmus, Yole's team lead analyst in Compound Semiconductor & Emerging Substrates said: "With LEDs, handset power amplifiers, and telecom & datacom, compound semiconductor went through its first inflection point with GaAs and InP in the 1990s".

As the demands for 5G connectivity, EVs, and fast chargers for smartphones come to the market, compound semiconductors will grow in both volume and market value, says Yole.

Looking into the future, e-mobility, including higher-voltage applications, sensing in various end-systems, the transition from 5G to 6G, and microLED displays will bring inflection points for different CS materials, along with more emerging substrates and new applications to come.

BOE invests $289 million in HC Semitek

BOE becomes largest shareholder as companies develop micro/mini LED partnership, says TrendForce

CHINESE FIRM BOE, one of the world's largest manufacturers of LCDs, OLEDs and flexible displays, has become the largest shareholder in Chinese LED company HC Semitek following a $289 million (RMB 2.1 billion) capital investment deal. The two firms are now working in partnership to develop their micro/mini LED businesses, according to market intelligence firm TrendForce.

BOE has been involved in micro/mini LEDs since 2017 and in 2020 established BOE MLED Technology as a subsidiary dedicated to the R&D and manufacturing of micro/mini LED products. As well as LEDs, HC Semitek also produces LED epiwafers and sapphire substrates.

According to data from TrendForce, HC Semitek took fourth place in the 2021 ranking of LED chip suppliers by external sales revenue. HC Semitek is also developing advanced LED technologies, including micro/mini LEDs. In a ranking of LED chip suppliers based on the revenue that is solely from sales of mini LED chips, HC Semitek is currently in third place, behind Epistar and San'an.

RGB microLED chips are already regarded as a key component among the leading brand manufacturers. Samsung has invested in PlayNitride in order to advance its microLED solutions. TCL CSOT has formed a joint venture named Xiamen Extremely PQ Display Technology with San'an. Another example is Ennostar's partnership with AUO and Innolux for the development of microLED displays.

For BOE, the HC Semitek investment should strengthen its already advantageous position in the field of micro/mini LEDs. Furthermore, in BOE's efforts to develop related technologies, HC Semitek is going to provide significant support going forward. For HC Semitek, the competition in the LED chip industry has become fiercer in recent years as suppliers such as MTC, San'an, and Changelight release new production capacity.

This year, the LED chip market has been challenging because of the resurgence of local Covid-19 outbreaks in China, the Russia-Ukraine military conflict, and ongoing global inflation. With a sharp drop in the demand for end products, the LED chip market has shifted to oversupply, and most LED chip suppliers now operate at a loss.

HC Semtek has been expanding into the high-end market segments, such as mini LED solutions and automotive LED solutions. However, this move has come at the expense of abandoning some parts of the low-end market segments. Therefore, the company has also lost some market share.

TrendForce's data reveal that HC Semitek's global market share for LED chips came to 7 percent in 2021, down by 2 percentage points from 2020.

TrendForce points out that BOE is among the investors that HC Semitek has targeted in its latest share placement. The proceeds are to be used to build a base for not only the production of microLED wafers but also the packaging and testing of microLED chips. This capacity expansion project, in turn, is expected to raise market share and generate profit for HC Semitek.

STMicroelectronics and Soitec cooperate on SiC substrate manufacturing technology

ST plans to ramp chip production for the automotive industry with Soitec's 200 mm substrates.

STMICROELECTRONICS and Soitec have announced the next stage of their cooperation on SiC substrates, with the qualification of Soitec's SiC substrate technology by ST planned over the next 18 months. The goal of this cooperation is the adoption by ST of Soitec's SmartSiC technology for its future 200 mm substrate manufacturing, feeding its devices and modules manufacturing business, with volume production expected in the midterm.

"The transition to 200 mm SiC wafers will bring substantial advantages to our automotive and industrial customers as they accelerate the transition toward electrification of their systems and products. It is important in driving economies of scale as product volumes ramp," said Marco Monti, President Automotive and Discrete Group, STMicroelectronics.

"We have chosen a vertically integrated model to maximize our know-how across the full manufacturing chain, from high-quality substrates to large-scale front- and back-end production. The goal of the technology cooperation with Soitec is to continue to improve our manufacturing yields and quality."

"The automotive industry is facing major disruption with the advent of electric vehicles. Our cutting-edge SmartSiC technology, which adapts our unique SmartCut process to silicon carbide semiconductors, will play a key role in accelerating their adoption," said Bernard Aspar, Chief Operating Officer of Soitec. "The combination of Soitec's SmartSiC substrates with STMicroelectronics' industry-leading silicon carbide technology and expertise is a game-changer for automotive chip manufacturing that will set new standards."

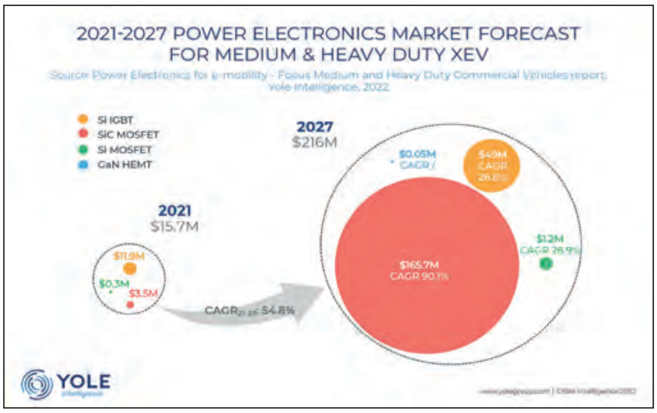
SiC is a disruptive compound semiconductor material with intrinsic properties providing superior performance and efficiency over silicon in key, high-growth power applications for electric mobility and industrial processes, among others. It allows for more efficient power conversion, lighter and more compact designs, and overall system-design cost savings – all key parameters and factors for success in automotive and industrial systems.

Transitioning from 150 mm to 200 mm wafers will enable a substantial capacity increase, with almost twice the useful area for manufacturing integrated circuits, delivering 1.8 – 1.9 times as many working chips per wafer.

SiC to service buses and trucks

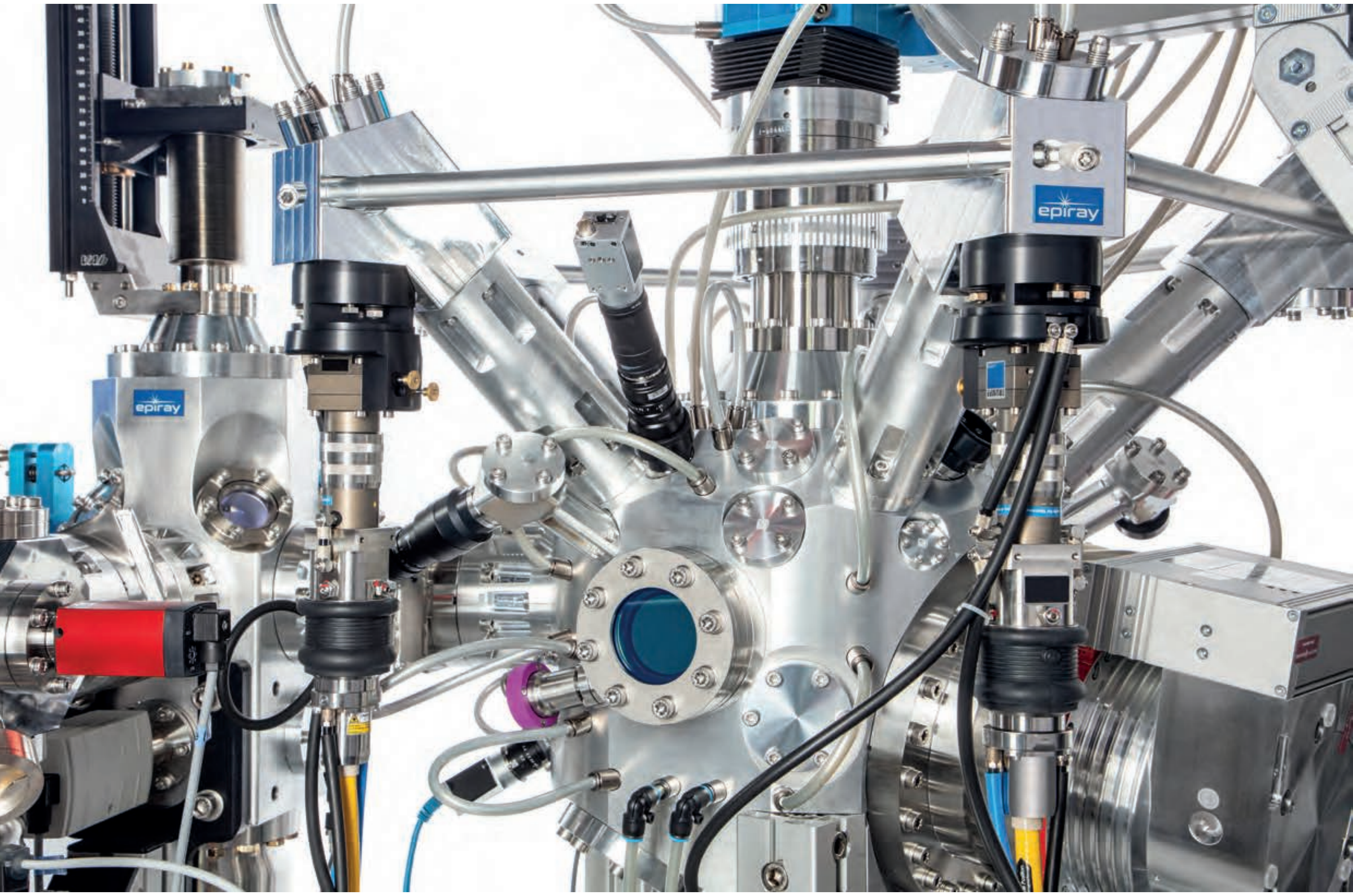
TRUCK AND BUS supply chains should benefit from passenger vehicle electrification. Medium and high-duty (M&HD) vehicles are close to the wide adoption of electrification. This segment will grow from 75,000 vehicles sold in 2021 to 436,000 in 2027, with a 34.1 percent CAGR21-27. The main growth comes from battery EVs (BEVs), just as happened in light-duty (LD) vehicles, including passenger vehicles and light-duty commercial vehicles, with a delay of 6 to 8 years.

Yole Intelligence has developed a dedicated report to provide an in-depth understanding of the changing automotive industry ecosystem and supply chain. In its new *Power Electronics for e-Mobility 2022 – Focus on Medium and Heavy Duty* report, the company, part of Yole Group, provides a comprehensive overview of the current technological trends and a 2021-2027 forecast in value, units, and wafers for M&HD vehicles, and gives key technical insights and analyses on future technology trends and challenges. For Tier-2 component suppliers, at least semiconductor suppliers, there is no distinction between LD and M&HD vehicles. Both segments increasingly require automotive standard devices configured at the sub-system level to meet specific requirements. On the one hand, M&HD vehicles can benefit from the rapid development driven by LD vehicles. On the



other hand, since the total volume is much smaller, it is more challenging to secure supplies. Although less vertical integration is seen in M&HD, several vehicle makers are manufacturing their own inverters and motors, at least.

Uniquely in China, some inverter suppliers exist specifically for M&HD vehicles. BEVs and fuel cell (FC) EVs will be the primary technologies for M&HD commercial vehicles, which also find synergy as FCEVs mostly use an electric powertrain of battery, inverter, and motor. New technologies, such as SiC MOSFETs, high-voltage system integration, and dedicated BEV platforms, are penetrating from LD to M&HD.



A new twist for MBE

Switching to laser-heated sources promises the growth of a vast range of films with exceptional purity

BY RICHARD STEVENSON, EDITOR, CS MAGAZINE

➤ Above: The epiray laser thermal epitaxy system is capable of growing a far wider range of materials than conventional MBE.

INVENTED IN Bell Labs the late 1960s, MBE is now a mature growth technique that's ideal for making pHEMTs, quantum dot lasers and numerous high-quality samples for academia.

Since its inception, tools for MBE have operated under the same principles – but that could soon change, thanks to the work of epiray, a spin-off of the Max-Planck-Institute for Solid-State Research in Stuttgart. This German start-up is pioneering a radically different approach to heating the sources that enable the growth of epitaxial films. Rather than placing material in a crucible that undergoes resistive heating – or using an electron-beam, if an element has a very low vapour pressure – epiray is advocating an approach that it describes as thermal laser epitaxy (TLE).

As well as the capability to heat elements to incredibly high-temperatures, this technique has many additional merits, according to Hans Boschker, epiray's CTO.

Boschker explains that during the growth of oxides, the presence of oxygen can cause the resistive heater to burn out. "This limits MBE to very low oxygen pressures, and limits the amount of materials you can grow."

Turning to the laser-induced evaporation of sources overcomes this restriction. "We are now only limited by intrinsic physics," remarks Boschker. "We can tremendously increase the materials space we're working on."

Another attribute of epiray's approach is that it is capable of growth rates spanning seven orders of magnitude.

Boschker and co-workers observed this when they investigated growth rates for aluminium. 30 W of laser power is sufficient to melt this element, and growth typically employs 80 W to 100 W, but it can be far, far faster when cranking the power up to 2 kW. Under those conditions, growth rates of 300 nm/s are possible.

epiray's approach to epitaxy also promises the growth of very pure films. That's because with conventional MBE, the heating of sources causes the crucible and its surroundings to get hot, contaminate the chamber and threaten to introduce impurities into the epitaxial films.

"We have the exact opposite," argues Boschker, who points out that with a laser, heating is restricted to just a small proportion of the source material.

He says that this approach also leads to "quite efficient" material consumption, and thus potentially low running costs.

To evaporate materials using the epiray approach, a 1060 nm laser is directed at the sources. "Metals absorb better at shorter wavelengths, so ideally we would use a blue or ultraviolet laser, but those don't exist in high power with the required beam quality," admits Boschker. So a compromise is adopted, which provides very good control of the optical output power, very high reliability and affordability.

Boschker believes that it makes little sense to begin by using this technique to try and replicate the growth of structures that are well-established by conventional MBE, such as the fabrication of distributed Bragg reflectors, which are formed by pairing many alternating layers of GaAs and AlGaAs. He advocates investigating materials that cannot be produced with the standard form of MBE.

At epiray they are pursuing this approach, looking at a range of materials for power electronics, including silicon carbide and gallium oxide. "Sapphire also looks very promising. Can we get doping into sapphire is a question for the future," remarks Boschker.

Laser ablation

epiray's development of its technology is somewhat accidental. After working in the field of MBE for many years, company CEO Wolfgang Braun joined a group specialising in laser ablation, which liberates material from a surface with incredibly short optical pulses that have a high energy density. Braun appreciated the elegance of using lasers to generate a source of material, but wanted to return to the physics of the MBE process, so married the two technologies.

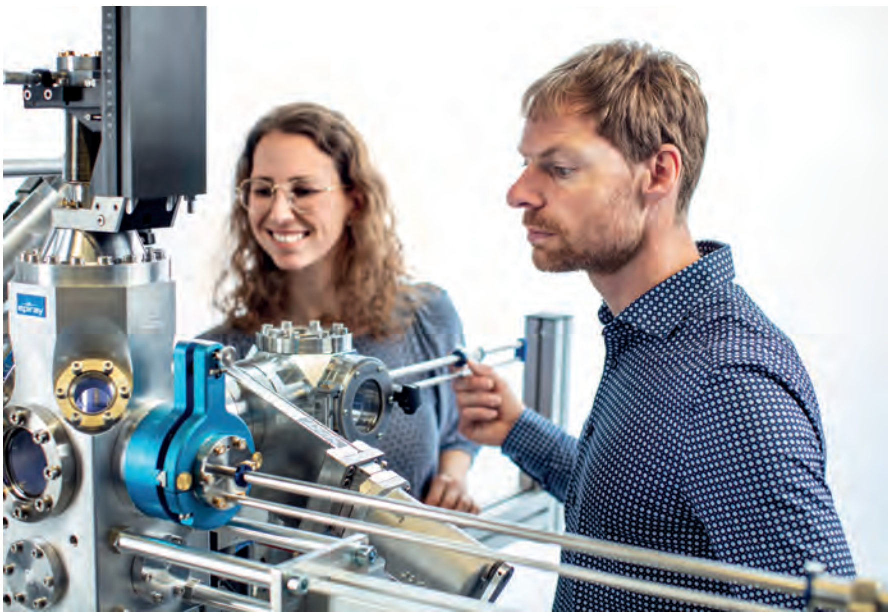
Financed through its own sales, epiray is selling TLE reactors featuring this technology, rather than just sources incorporating laser-based evaporation. At first glance that may seem an odd decision, requiring a more involved approach to getting to market. However, there is a lot of good sense behind this move.

One key consideration is that it's incredibly challenging to upgrade a conventional system with epiray's technology, partly due to a lack of space that leads to compromised efficiency. What's more, traditional MBE reactors use ports from below for the sources, while ports from above are needed to allow the laser to target the source.

Another issue relates to safety. With a high-power laser, it's imperative that radiation doesn't exit the tool and damage the eyesight of the user. "If you build your own system from scratch you can mitigate this, by essentially not having windows at all," says Boschker.

The company's business strategy is to initially focus on selling TLE tools to researchers operating in as many different scientific fields as possible. This will hopefully lead to the use of this growth technology for industrial production.

To support this vision, those that are interested in the technology can begin by spending time within the solid-state quantum electronics department to see how this system works. "Frankly, nobody is spending money on a new technology without seeing it in action," reasons Boschker, whose understanding of the needs for growers of thin films will surely help the prospects for this technology to redefine what's capable with MBE.



➤ Using a laser to heat sources enables a range of growth rates that span seven orders of magnitude.

Onsemi ramps SiC production

To meet the massive hike in demand for SiC power electronics, Onsemi is cranking up its capacity for producing SiC substrates and epiwafers

BY RICHARD STEVENSON, EDITOR, CS MAGAZINE

Within our industry the sector that's attracting the most attention is SiC. Sales of these chips are increasing at a phenomenal rate, due to tremendous demand from the makers of electric vehicles, as well as a ramp in the deployment of these devices in energy infrastructure, where they enable an increase in efficiency.

To cater for accelerating demand and to swell sales, makers of SiC devices are expanding their production capacity. Efforts underway include that by multi-national silicon and SiC chip producer Onsemi, which recently announced plans for substantial increases to its capacity for producing SiC boules, making and polishing SiC substrates, and for the growth of SiC epiwafers.

The majority of this increase in capacity will be used for internal chip production, according to Asif Jakwani, Senior Vice President and General Manager of the company's Advanced Power Division, which is part of the Power Solutions Group. He remarks: "We are a fully integrated IDM, especially in silicon carbide and silicon, and we want to have the ability to supply our own substrate."

Supporting this plan is Onsemi's acquisition, in late 2021, of SiC boule manufacturer GT Advanced Technologies, which has facilities in Hudson, New Hampshire. "We have acquired a second building within the same area, and those two buildings are driving the expansion for silicon carbide."

Onsemi is also expanding capacity at its site in Roznov, Czech Republic, that provides SiC wafer polishing and epitaxy; as well as silicon polishing, epitaxy and die manufacturing.

At this site, which introduced SiC processing in 2019, investment totals $150 million, and there are plans to spend an additional $300 million through 2023.

Onsemi has not broken down exactly how that will be spent. "But I can tell you that the majority of our capital investment is directed towards silicon carbide," reveals Jakwani.

Driven by this investment, there should be a 16-fold expansion in SiC wafer and epi-growth capacity at the SiC fab in Roznov by the end of 2024.

The staggering level of expansion will be supported by purchasing of tools that provide wafering, slicing, polishing and epitaxy.

Towards 200 mm

Today, as is the norm within the SiC industry, production of diodes and transistors is based on substrates that are 150 mm in diameter. However, Onsemi is putting the foundations in place for a migration to the 200 mm platform.

"Our CEO announced in quarter one of this year that we had produced a 200 millimetre diode wafer at our Bucheon facility," comments Jakwani, who adds that all the equipment that is being bought is convertible to this larger size.

"Initial production will be 150 millimetre, but our plan is to convert all that equipment to 200 millimetre."

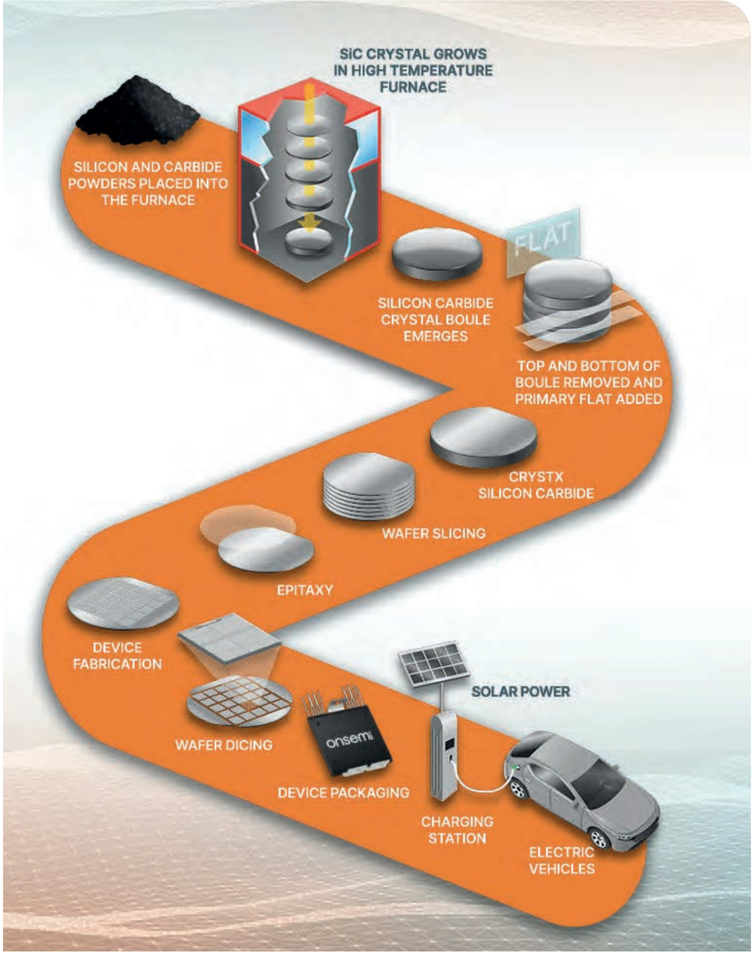
Expanding SiC capacity, by investing in more tools capable of processing larger wafers, should ensure higher margins.

"Economies of scale dilute your fixed costs and enable better utilisation of equipment," argues Jakwani, who points out that when a fab has more processing equipment, this minimises the constraints that occurs as the wafer moves through the line.

SiC has advanced considerably since the turn of the millennium, when the first Schottky barrier diodes appeared on the market. However, there is still a long way to go for this industry, reasons Jakwani: "If you can imagine silicon 50 years ago, silicon carbide is still in fair infancy."

He anticipates that as the industry moves from 150 mm wafers to 200 mm variants, improvements will be made to the quality of material, to epitaxy, and to fab equipment. He also expects to see refinements to the processes that are employed, and the device structure.

Like many of its peers, Onsemi is a vertically integrated manufacturer. That brings benefits, says Jakwani, including the opportunity to pinpoint the cause of a defect, which could be traced right back to crystal growth. Once the cause is addressed, yield increases.



➤ Onsemi is a vertically integrated manufacturer of SiC devices. Production begins with the growth of SiC boules, which are sliced and processed into substrates.

The expansion at the Roznov site is expected to create 200 jobs by the end of 2024.

"We are taking some of our best people in silicon and migrating them to silicon carbide," says Jakwani, who points out that this transition will be aided by those engineers' experience in IGBTs, which often operate at high currents and voltages.

An increase in the workforce will also be supported by hiring engineers from within the semiconductor industry, and working with universities, with internships helping to attract new talent.

"With all those efforts, we are able to cultivate a good, solid workforce, which is very critical for us to be the leader in the industry."

SiC has advanced considerably since the turn of the millennium, when the first Schottky barrier diodes appeared on the market. However, there is still a long way to go for this industry.

Plasma Polish enables SiC revolution

New lower-cost specialist SiC polish technique provides epi-ready surface, without compromising quality

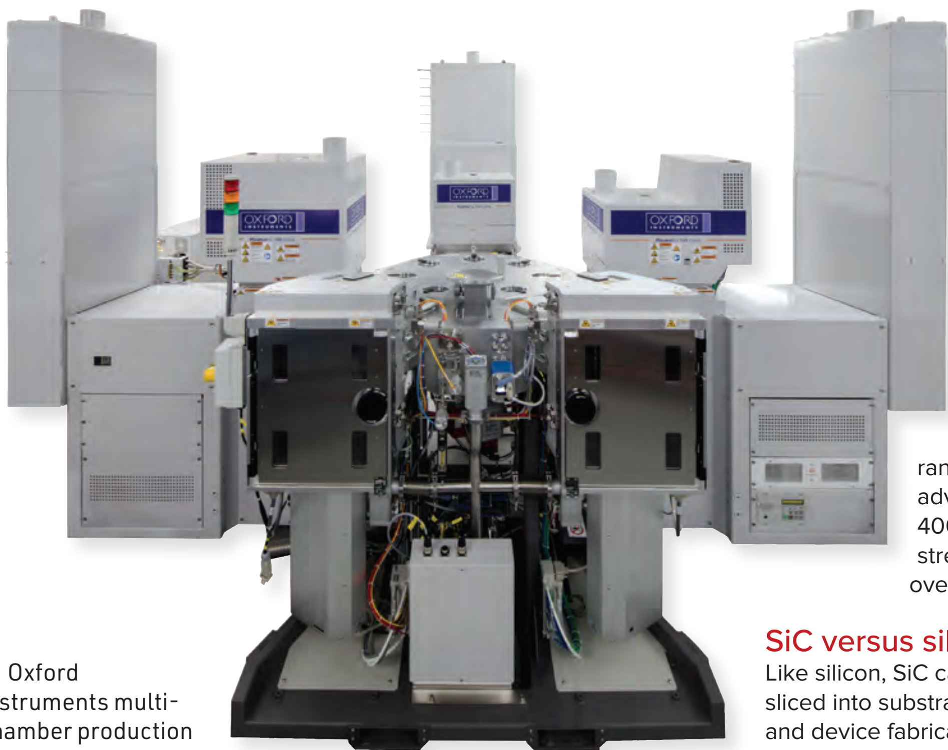
BY GRANT BALDWIN FROM OXFORD INSTRUMENTS PLASMA TECHNOLOGY

ELON MUSK is not a paint-by-numbers operator. Instead, he's leading the commercial space race, he's playing the crypto currency game like a grandmaster, and he's just closed a Twitter purchase deal that's been a white-knuckle ride for investors and representatives of the microblogging social network site.

Musk is as interesting as he is shrewd. He has a propensity for pushing boundaries, exemplified by his automotive jewel Tesla, pioneer of the electric vehicle (EV) market, and the first adopter of SiC inverters. At the heart of every EV is a drive train inverter, normally operating at 400 V, that converts DC battery output into an AC form that propels the vehicle. SiC had an early adopter in Tesla, bringing it recognition as the material of choice for this class of application. This has spawned broader adoption and ramping demand for this advanced compound material – also making it commercially attractive at today's device price point.

Cost aside, the automotive industry is a conservative market that does not move quickly. Reliability must be proven, so rushing innovation is imprudent, considering the preciousness of the cargo. However, the importance of SiC components in E-mobility, as well as in other sectors, such as solar and industrial markets, is prompting the makers of these wide bandgap devices to develop enticing new technologies and processes to meet the performance, reliability and volume demands of these markets.

There are still some high-end vehicles that utilise the alternative silicon IGBT, but the number of models adopting this form of transistor is vanishingly small and diminishing rapidly. At 400 V operation SiC is very proficient, but will not dominate there because silicon is still quite strong in that space. At 800 V operation using 1200 V rated devices, SiC demonstrates far faster switching speeds than the silicon IGBT – leading to lighter, more efficient and smaller inverters, with fewer cooling requirements. Drawing on all these strengths is key to trimming the battery size required to extend the target range on a single charge. These advantages, already apparent at 400 V, are magnified at 800 V, strengthening the argument for SiC over silicon.



➤ Oxford Instruments multi-chamber production equipment

SiC versus silicon

Like silicon, SiC can be grown in boules. They are sliced into substrates ready for epitaxial growth and device fabrication. The SiC industry is currently ramping production of diodes and MOSFETs, and in time this portfolio could be extended to include IGBTs and thyristors.

Due to the comparable nature of SiC and silicon, their devices bear striking similarities. However, SiC offers higher performance, and there are also cost variations when comparing at both the unit and the system level. One key difference is the cost associated with wafer fabrication – this is far higher for SiC, because it's an incredibly hard material. There are also some SiC-specific techniques, such as the gate fabrication process, required to get channel mobility as high as possible, and the final wafering step prior to epi. For the latter there's now a new process from Oxford Instruments called Plasma Polish – more on that below.

➤ Etch, deposition and thermal growth module options

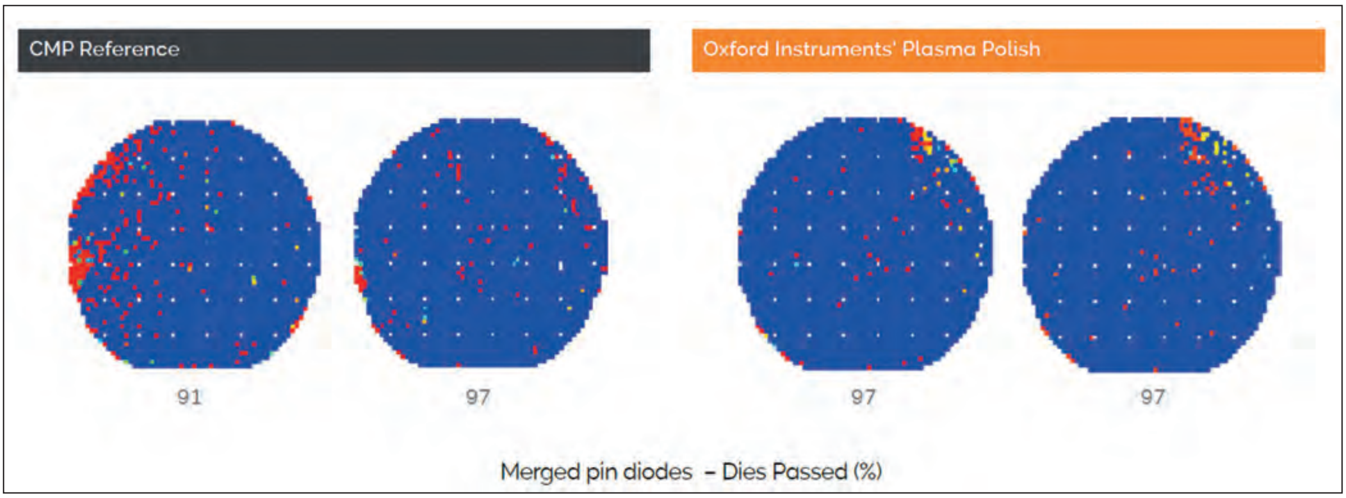
By far the biggest cost is energy. It is incurred right from the start and is embedded in the wafer from very early in the wafering process. Silicon can be grown cheaply and easily, because this process requires a modest amount of energy, compared with SiC, to liquify the silicon and make boules. Silicon boules, cylindrical crystals that are sliced into wafers, can have diameters of more than 300 mm and a length of more than a meter.

In stark contrast, bulk SiC is produced via a seeded sublimation process, which is very slow compared to silicon, taking up to a week to produce a 150 mm diameter boule – although 200 mm is on the way. Production is incredibly energy intensive, with the high costs embedded in the bouling process carried through to device costs.

The cost benefit of shifting SiC production from 150 mm to 200 mm wafers is based on the principle that the larger diameter allows more devices, making each wafer more valuable. However, it's important to note that the energy cost increases proportionally with the wafer surface area, so while 200 mm SiC is certainly essential to advance its wider adoption, when trying to reduce cost per device for SiC, it's no magic bullet.

What's slowing adoption?

The strongest headwinds to the deployment of more SiC devices tend to be associated with costs, but there is also additional effort required to make the switch from silicon to SiC for OEMs. Reliability, robustness, efficiency and performance are all cost drivers that really matter to the automotive industry. Every maker of EVs has a SiC development programme, as this material is widely regarded as key to the rollout of this class of automobile. A key consideration from consumers



➤ Yield data highlights that the Plasma Polish process developed by Oxford Instruments delivers a device yield of SiC merged *p-i-n* diodes that is at least as high as that resulting from CMP.

At surface level, CMP has a positive effect on improving material quality ready for epitaxy, but the additional polishing force required to improve the top surface can negatively impact the subsurface. Too much mechanical pressure and friction-generated heat can cause micro fissures to form in the sub-surface

driving the switch to SiC is increased range on a single charge, while looming political deadlines, such as California's internal combustion engine ban that's expected in 2035, is accelerating mass EV adoption.

The current silicon solution is cheap, its properties and engineering limitations are well understood, and despite automotive OEMs being one of just a handful of industries with deep enough pockets to fund this type of development, new devices need to be robust and price competitive. However, as 800 V inverters expand from the likes of the Porsche Taycan and the Audi e-tron GT to the majority of EVs, SiC will start to become the more obvious choice over the silicon IGBT. Once mainstream vehicles start to pack SiC technology, the tide will have turned for sure for SiC over silicon.

Power generation cost per unit in some circumstances can be as much as five times higher for SiC compared with silicon. Shifting to 200 mm and benefiting from the associated economies of scale should enable the price to come down, but further progress will require a reduction in both substrate fabrication cost and epi cost, as they are the two most expensive processes after the boule is formed. The key point is that a move to 200 mm wafers may not be the panacea some believe it to be. It's all about energy, and this energy cost is embedded into the 200 mm boule. Consequently, when taking all factors into consideration, if SiC devices are to achieve cost parity with silicon, 200 mm wafer capability will have to go hand-in-hand with SiC-specific advanced substrate fabrication techniques and solutions.

➤ The AFM by Oxford Instruments Asylum Research offers an insight into surface morphology. This tool provided an image of the surface of a SiC wafer, used on the background of the front cover of this magazine.

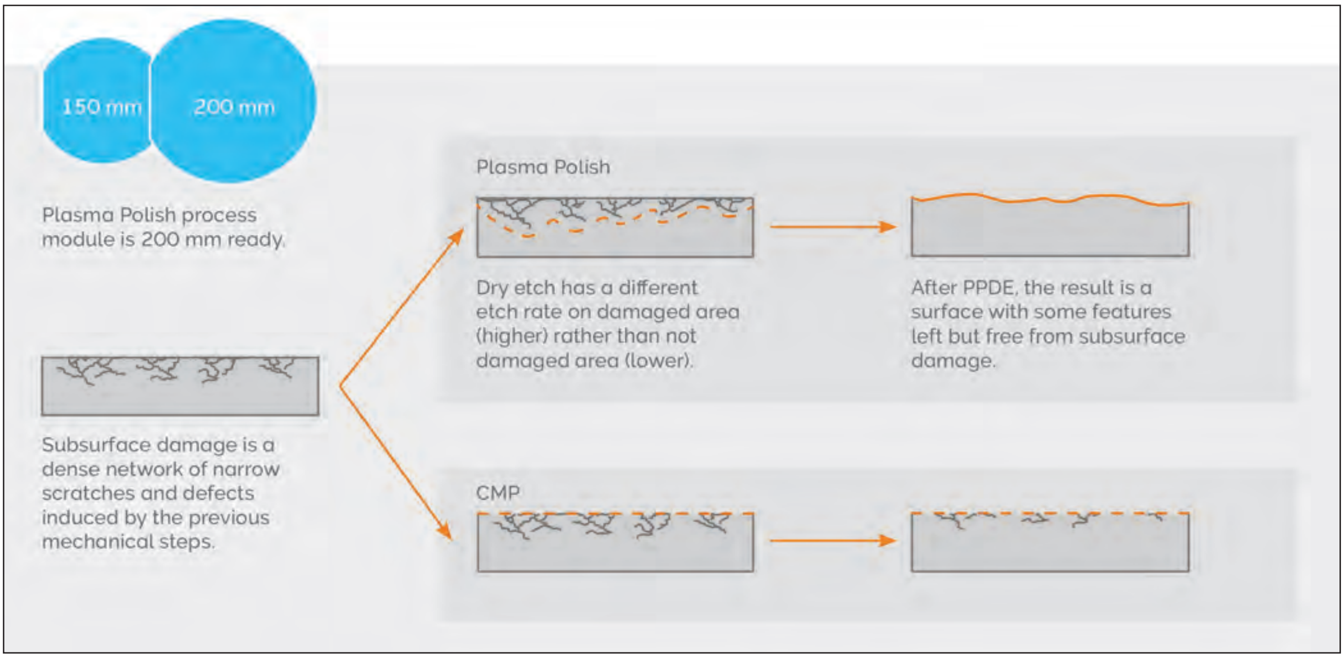
Advancing fabrication

At this year's International Conference on Silicon Carbide and Related Materials (ICSCRM), held in September in Davos, Switzerland, our team at Oxford Instruments Plasma Technology launched a Plasma Polish process for SiC substrates. Our new process is cleaner, greener and more cost-effective than the incumbent, chemical mechanical polishing (CMP). Plasma Polish can be implemented as a direct plug and play replacement for CMP, fitting neatly into the space where CMP currently sits.

There are three key steps in the process for creating substrates ready for epitaxial growth and subsequent device fabrication. Those critical steps are: boule growth; slice and grind; and then polish. The purpose of the polish is to reduce the SiC surface roughness to a point where it is sufficiently smooth for epitaxial growth.

CMP achieves epi-ready smoothness by applying rotating abrasive discs to the surface of the substrates with pressure. This is accompanied by proprietary, expensive slurries, which chemically treat the surface. To prevent clogging during this process, flushing removes material from the discs. CMP is well-established, having been used for many years to achieve epi-ready smoothness, but it suffers from some limitations that are overcome with Plasma Polish.

One substantial limitation is the use of slurry, an expensive component to acquire and dispose of afterwards, as it is a semi-toxic by-product. Additional costs arise due to the need for lots of water – as much as 40 percent of water usage throughout the semiconductor fabrication industry is associated with CMP. Lastly, there is the requirement to regularly replace the abrasive discs, which adds cost and supply chain complexity.



Another issue is the suitability of CMP in relation to yield for SiC devices. While CMP has undoubtedly been a great success for processing silicon, is it the ideal process technique for harder semiconductor materials? As SiC is one of the hardest materials used in any industry, it requires more mechanical pressure during the polish step than silicon.
At surface level, CMP has a positive effect on improving material quality ready for epitaxy, but the additional polishing force required to improve the top surface can negatively impact the sub-surface. Too much mechanical pressure and friction-generated heat can cause micro fissures to form in the subsurface, which are not ideal for material quality and can cause lower device yield.

Our approach offers an attractive alternative that can accelerate SiC adoption by combining high-quality results with a reduction in cost. It is a dry-etch process, taking place in a chamber held at a low pumping pressure. A chemically reactive plasma is accelerated onto the wafer surface with electromagnetic force, leading to chemical and physical removal of the material. There's no need for slurry or water (other than recirculated cooling water), and thanks to the absence of moving or wearing parts, consumable costs are minimal compared to CMP.

As it is contactless, no physical pressure is applied to the wafer during Plasma Polish, so sub-surface damage is actually improved. The gas in the Plasma Polish process also has a lower density than the slurry used in CMP; and it is electromagnetically accelerated onto the wafer surface, rather than squirted on, as is the case for a slurry with CMP. These key differences enable the Plasma Polish process to penetrate deeper into the damage left behind by the slice/grind wafering step. The plasma physically knocks off and chemically attaches to the weakly bonded and damaged SiC surface and sub-surface. The material that remains is more strongly bonded and therefore higher quality, making it preferable for higher-yielding devices.

Our SiC Plasma Polish tool, which is suitable for processing 200 mm wafers, has been configured to 150 mm during process development. Plasma Polish is a great addition to our established portfolio of production tools for 200 mm wafers.

➤ Plasma Polish penetrates into the sub-surface, repairing damage.

➤ Ballroom and through-wall cassette load configurations are available

Over the years, we have transferred many processes to larger sizes, as wafer diameters have increased. We understand the process transfer well, but it's just a lack of commercially available 200 mm SiC substrates that is preventing Plasma Polish at 200 mm.

Too good to be true?

When we announced our Plasma Polish technology at the recent ICSCRM, a few delegates wondered if it sounded a bit too good to be true. A little bit of scepticism is certainly healthy, but we would argue that our solution falls into the category of 'why didn't someone think of it sooner?'

Rather than debating pros and cons, we simply share our validation data, which speaks louder than words. This data comes from an investigation carried out in partnership with the Scottish specialist SiC wafer foundry Clas-SiC Wafer Fab, where we ran Plasma Polished and CMP-treated wafers side-by-side to device production.

The performance of merged pin diodes and 1200 V MOSFETs is comparable, or arguably slightly better for the Plasma Polish process. This led David Clark, Technology & Customer Relations Manager at Clas-SiC, to comment that Plasma Polish is a very important technology for reducing the cost of SiC-based power converters and increasing their adoption.

We have also identified further uses for the Plasma Polish process. It can be utilized by SiC boule manufacturers, to prepare the underside of the SiC seed wafer in preparation for the sublimation process.

Currently that wafer surface is processed using CMP, so there are opportunities for cost savings and improvement to material quality there. In addition, Plasma Polish could be applied to semi-insulating undoped SiC substrates used for RF applications, as well as several other applications that our developers are keeping under wraps for now.

The rubber meets the road

A single technological advance will not be enough to bring SiC to mainstream adoption. What's needed is to stack several marginal gains to reach the tipping point for this advanced material. It's essential to think beyond the silicon processing techniques that worked well for that material, because SiC has fundamentally different properties and performance.

We are now a step nearer. We are on the cusp of 200 mm capability, along with a new technology for wafer polishing that's cleaner, greener and cost-competitive. Once this is combined with other SiC-specific processing techniques, the foundations will fall into place for an E-mobility and sustainable energy revolution.

IQE's crystal clear vision for growth

Streamlined manufacturing and expanding into new materials are two key elements in the strong growth strategy of IQE's new CEO, Americo Lemos.

INTERVIEW BY RICHARD STEVENSON, EDITOR, CS MAGAZINE

RS: *You have taken over from Drew Nelson, a charismatic driving force behind IQE, who led this company for many years. Those are big shoes to fill. Is it daunting to step into them?*

AL: Drew has done a great job. He created the company and led it for 33 years. IQE has evolved, and delivers fantastic technologies to great customers and markets. So Drew deserves a lot of respect.

Drew and I are good friends. We work together. He's a board member of IQE, and I look forward to building on his legacy.

RS: *What attracted you to taking the position of CEO of IQE?*

AL: When I was in my previous role at GlobalFoundries, I understood that in the new world we live in semiconductor manufacturing is more and more critical, even vital. We experienced a chip shortage recently. I think it's the first time that the semiconductor industry ran into a shortage. So I understood the criticality of manufacturing. If you consider geopolitics, it clearly demonstrates that we need to improve or restructure semiconductor manufacturing companies, like Intel, coming into the pure-play manufacturing space. Therefore, I found IQE a very interesting place to bring all my knowledge, and take it to a growth trajectory.

RS: *Why do you think your background gives you the skills and experience to thrive in this role?*

AL: I have a background from technology to business to strategy, and I have a pretty good understanding of the technology space. I have worked from the full-product and handset space to platforms, chipsets, fabless and silicon foundries, and now compound foundries. So, I'm one of the very few that's fortunate to have gone through the entire ecosystem of technologies, from full-service product to the material level. That gives me a unique perspective of what my customers are dealing with – my customers being product companies, or fabless or foundries. I'm able to connect with their challenges, understand what value means to them, and really help bring solutions.

RS: *It's coming up to a year since you've been appointed CEO. What have you achieved so far?*

AL: When I came on board I said that my first focus would be on the commercial aspects of the business. I think IQE has three fundamental strategic advantages. One, we have the most complete technology

➤ Americo Lemos began his career as an engineer in the telecom sector in France. He worked in Silicon Valley for about 25 years, and has experience in China and the rest of Asia.

roadmap, by far, in epitaxy in the compound industry. This is a unique competitive advantage. Second, we have a global footprint that is extremely important to our customers in today's world. Third, we have the ability to scale, more than anybody else in this industry. The recent shortage has demonstrated how critical scaling is.

Up to now, IQE has been developing great technologies, and pushing those technologies to market. When I came in I said we need to reverse that strategy, and create a pull from the market. We have to have a roadmap that is better aligned to what the market and customers want, and start building commercial models that are more resilient for the business.

Since I joined we have transformed our commercial engine. We have announced some commercial deals, long-term agreements and technology partnership with customers. It is important to provide visibility to industry and to investors.

RS: *What are the biggest challenges of running an epiwafer provider that operates in multiple markets, with sites all over the world?*

AL: It's actually an advantage, more so today than ever before. Back in the day it was always more economic to have a single site located in Asia. Today it's no longer the case. Today the value comes from providing a secure, resilient supply chain to industry and to our customers. This is what IQE is: we are the only pure-play epitaxial provider that has a global footprint. To me, this is a strategic advantage.

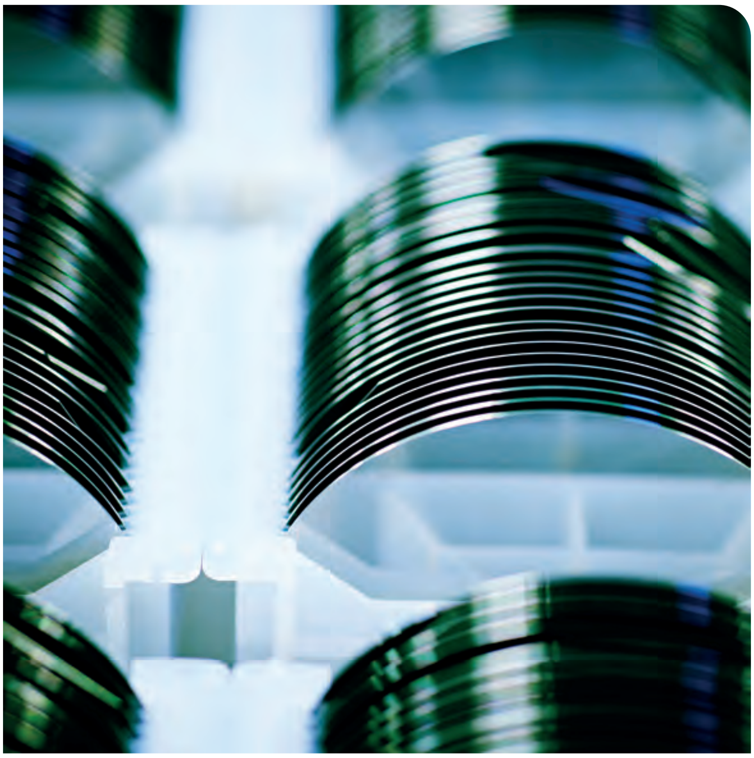
RS: *You're consolidating your epi fabs. What's the thinking behind that and how's it going?*

AL: Having a global footprint is a strategic advantage – but we still have to rationalise our footprint. The goal is to have an optimum footprint.

We now have one site in Asia, which is Taiwan. We have closed the Singapore facility and moved that capability to Taiwan. We want to have two sites in the US, Massachusetts and North Carolina, for MOCVD and MBE, respectively. We are consolidating Pennsylvania into North Carolina, to create a world-class MBE facility. And we will have one large site in Newport, with St Mellons turning into an R&D facility. When it comes to MBE, we'll do R&D in North Carolina, as it's just not economically viable to put MBE into St Mellons.

RS: *Sales to the wireless sector tend to provide just over half of IQE's revenue. The smartphone accounts for the lion's share of this. Its sales are sluggish, but 5G requires a lot of GaAs content. So where does this leave you?*

AL: The wireless space is subject to cycles. To minimise the impact of these cycles, we try to focus on value, so premium and high-end-segment



➤ IQE has developed a process for producing VCSELs on 200 mm germanium wafers that could underpin rapid growth in volumes in this market.

5G products. We are also working really hard to diversify our customer base and our product mix.

At the same time, we are seeing potential growth in the WiFi 6 type of product. The IoT segment will also grow to become a lot more smart. Some companies are saying they're going to transform IoT into 5G connected devices that could do AI processing, because data shows that more than 60 percent of AI processing is done on the edge. Therefore, you need to add compute and connectivity capabilities to those IoT devices. That could potentially generate orders for our products in the coming years.

RS: *Back in 2017 IQE bought a site in Newport to stablish a mega-foundry with a capacity for up to 100 MOCVD tools. How many MOCVD tools are installed today, and what products are you producing on this site?*

AL: This facility is where we intend to grow our business in a significant way. We can grow by ten-X.

Our installed MOCVD tools are currently producing many products, including VCSELs. It is a great state-of-the-art facility, structured to grow in modular fashion. We can keep scaling without disrupting existing businesses, by and large. Having the UK facility is also great from a geopolitical perspective, because it allows us to address multiple markets.

RS: *The VCSEL is a very important product for IQE. With makers of Android phones tending to ditch this laser, and lidar for autonomous vehicles still some way off, are VCSEL sales growing slower than IQE anticipated?*

IQE would like to position itself as the epitaxial supplier for the industry. Whichever technology wins, we want to be able to offer the epitaxial requirements, which we believe would be huge, in terms of demand. That's why facilities like Newport are really, really suitable for scaling

AL: The VCSEL is driven by a great ecosystem of customers. We recently announced a partnership with a 3D sensing company that would allow us to increase our market. My vision is that at some point we should enable every camera out there to have 3D capabilities. Imagine if every camera on your phone, on your house, on drones and in your computer had 3D capabilities.

We need to provide the scaling, and the economics that go with it. That's why moving from 6- to 8-inch wafers is a very important step. We announced this summer that we had available an 8-inch VCSEL wafer, so we can unlock a fantastic market.

RS: *The microLED could be a great opportunity for IQE. It's a technology with a lot of promise – maybe bordering on hype. How do you see the future for this class of device?*

AL: Everybody in the industry believes it's going to happen, but it is very challenging to point out when, which device class, et cetera. We have to remember the challenges: climate change, inflation, energy costs. In any device, the largest element that consumes power is the display. As we go into a digital economy where everything has to be displayed, we ought to think how can we bring the most energy-efficient technology to market. That might be a driving force for the microLED.

We are seeing numerous competing technologies in the marketplace, and we are partnering with many technology companies and ecosystem players. We have announced partnerships with Porotech and Micledi. We are also working with players that we have not made public.

➤ The Newport wafer fab has space for around 100 MOCVD tools. This facility could be used to support a ramp in production of optical products, such as VCSELs.

The market is going to happen, but there are different schools of thought. One is that it starts from large displays, like signage-type products. Others see it starting from very small displays, like contact lenses. Some believe AR/VR will be the leading form factor, because there's no competing technology against microLEDs in that segment of devices. There is tremendous investment being made – from technology to manufacturing, to the design, to the product – for that type of microLED segment.

IQE would like to position itself as the epitaxial supplier for the industry. Whichever technology wins, we want to be able to offer the epitaxial requirements, which we believe would be huge, in terms of demand. That's why facilities like Newport are really, really suitable for scaling.

RS: *Within the compound semiconductor industry, power electronics is enjoying great success. How could IQE benefit from that?*

AL: This is our next growth vector. When I came in at the end of March, I announced that we're going to play in a few verticals. One, obviously, is smart devices. Another is infrastructure and data centres, with photonics. The third is automotive, with light and power electronics; and then there is the industrial market for power electronics and aerospace, et cetera.

Power electronics has obviously two components to it. There's silicon carbide, which is by-and-large a vertically integrated market today. But GaN power is very important. Recently, we announced our partnership with SK siltron, to develop GaN for power electronics, and for radio frequencies as well. So, we are making a lot of investment into GaN power electronics. We see this as a tremendous opportunity for IQE, and we are engaged with many customers and partners to deliver GaN into the power electronics market.

We want to be able to offer versatile GaN platforms that address customer's need in terms of RF, in terms of power electronics, and in terms of the microLED. All three growth megatrends rely on GaN technology in some shape or form.

As we develop these GaN technologies, we want to grow the geometries to 200 millimetre and later 300 millimetre. So compounds will have to adopt some silicon technology knowhow. We need to go mainstream – and to go to mainstream, we need to go to where the silicon space is, which is delivering high volume, large geometries and high efficiencies.

RS: *In the UK, electricity prices are sky high. Growing epiwafers by MOCVD requires a lot of energy. Do you have to pass high costs on to your customers?*

AL: We are facing inflation in the UK, more so than other places. But as a global epiwafer supplier, we are able to mitigate some of this by shifting our manufacturing from one site to another. We are also looking for efficiencies: How do we do things better? And third, some of the increase can be passed to customers.

We are having conversations with our partners in the ecosystem. I think that the recent chip shortage, the supply chain constraints, and the geopolitical challenges have really changed the nature of conversations. It's no longer left to supply-chain teams. Very often C-level executives are taking charge of some of those conversations, to make sure that we build a secure, resilient supply chain first, and then figure out how to make the economics as best as possible. It's an ongoing effort.

RS: *Over its history, IQE's share price has experienced dizzying highs and incredible lows. In recent years it's been relatively stable. How close an eye do you keep on the share price, and how much does it matter to you?*

AL: As a public company it does matter. But I have to keep my focus on the business that drives the share price. My view is that we are going to have to focus on growing the business in a more resilient and predictable way; grow our margins to where we should be, compared to peer groups; and then communicate.

It is important that we communicate. That has not been done enough. Now we are doing it better. Since I joined, the way we communicate is a lot more business than technology focused. We're going to continue doing that, and we're going to build a business that is based on sustainable growth, in terms of customer mix and product mix. We're going to continue to create value to our three vectors: our competitive technology roadmap, our global footprint, and our ability to scale the business with our customers. It's a lot faster for any customer to come scale with IQE, as opposed to building on a green field, which is twelve to 24 months later at best.

RS: *Investors in IQE don't tend to be paid a dividend. Does this need to change?*

AL: We do not plan to change. At the moment we are a growth business, so we still continue to invest for the growth of the business.

Showcasing MBE's credentials for high-volume production

Whilst MBE may be renowned as the best tool for growing research samples, it has another string to its bow: it is the preferred technique for manufacturing of a number of different devices

BY RICHARD STEVENSON, EDITOR, CS MAGAZINE

WE ALL MAKE GENERALISATIONS. At times we'll get pulled up on this, with those around us pointing out examples of outliers and picking holes in our arguments. But despite this admonishment, we will soon revert to our old ways. After all, when trying to make plans and draw conclusions, spending too much time considering the cases that don't fit in makes it nigh-on impossible to construct a line of reasoning.

It's probably for this reason that some of us will categorise the growth techniques in our industry in an overly simplistic way. Many of us may view MOCVD as the technique for high-volume production, and see MBE as the epitaxial technology for making samples for research, such as novel quaternaries and variety of electron and hole gases. But the reality is that MBE is also a tool for volume production.

This point was well made by two of the plenary speakers at the most recent International Conference in MBE, held in Sheffield, UK, from 5-9 September.

MBE for epiwafers...

Speaking at this conference – the latest in a series that dates back as far as 1978, when the inaugural meeting was held in Paris – IQE's Amy Liu championed the diverse use of MBE for producing a variety of compound semiconductor epiwafers.

Liu, Vice President of IQE's US R&D Programmes, kicked off her talk by pointing out that MBE has a strong track record in producing devices, dating back many decades. Early successes include the fabrication of a GaAs laser at Bell Labs in 1972.

The US is also the birthplace of the world's first MBE epi-foundry, Quantum Epitaxial Design. Launched in 1988, this trailblazing firm merged with UK-based Epitaxial Products International in 1999 to form IQE, today's multinational powerhouse for the production of epiwafers.

IQE currently has two sites in the US with MBE capability. There's the facility in Bethlehem, Pennsylvania, where Quantum Epitaxial Design was born; and the former RFMD facility in Greensboro, North Carolina. Consolidation is in the pipeline, involving the relocation of MBE tools at Bethlehem that are used to make a variety of infrared and III-V-on-silicon structures to the Greensboro facility, which produces GaAs wireless and photonics epiwafers.

Liu remarked that initially shipments for making GaAs-based wireless devices, such as pHEMTs, dominated the market for MBE epiwafers. However, she expects that over the coming years this market will become more diverse.

To drive down costs and boost productivity, IQE employs MBE reactors that can accommodate multiple wafers. These growth tools can house as many as 23 wafers with a 75 mm diameter, or 9 with a 100 mm diameter. Following growth, epiwafers are scrutinised by what Liu refers to as a "full suite of material characterisation tools".

The two types of epiwafer that have been manufactured in the largest volume for the wireless sector are those for making pHEMTs and HBTs. While pHEMTs are no longer deployed in handsets in the volumes of yesteryear, HBTs are still widely used in mobile devices for amplifying RF signals, maintaining this sector's position as the killer RF application.

With volume production at IQE dating back decades, it's no surprise that engineers have established very mature processes on well-used tools. Liu described growth on a 7 x 150 mm platform, where 6300 runs yielded 44,000 epiwafers.

Volumes for IQE's photonic products are smaller than those for GaAs wireless, but still significant. Like that for GaAs products, production incorporates statistical process control, but with growth typically on smaller substrates. For example, 75 mm substrates are used for making epiwafers for InGaAs photodetectors. The company's technology portfolio also includes the production of epiwafers for InP-based edge-emitters spanning 2.1 - 2.4 μm, with good uniformity claimed on 100 mm substrates; and GaSb photodetectors, which have seen a sharp increase in demand over the last few years, according to Liu.

US department of Defense programmes have helped our industry to increase the maturity of GaSb-based devices, via efforts to increase the size of the substrate. Thanks to this, GaSb substrates initially expanded in size from 50 mm to 75 mm and then on to 100 mm. Now epiwafer production by MBE can even take place on a 7 by 125 mm platen.

Liu shared device data for GaSb-based epiwafer production at both the Bethlehem and Greensboro sites. Evaluating material with a Surfscan 6220 revealed that all the epaiwafers are free from major defects, with defect densities well below the specified requirement. The growth process is said to be good, reproducible, and offering good control, with run-to-run repeatability.

As well as producing wafers for single-band detection, IQE is starting to make variants with dual-band detection. As one might expect, volumes for the latter are lower.

Liu also outlined plans for the future, discussing what is in the company's pipeline, and which technologies have near-term potential. For the development of new materials and processes, IQE

Morris dancers provided entertainment at the ICMBE conference dinner, held at The Cutlers Hall, Sheffield. This narrow Georgian three-storeyed building is home to a collection of knives made from steel, an important material for making MBE tools. Credit: Laure Divisia.

ICMBE's conference chair, David Ritchie, is Professor of Experimental Physics at the University of Cambridge, and Professor of Semiconductor Science and Technology at Swansea University. Credit: Laure Divisia.

now uses reactors with high-volume capability from the outset. Illustrating this point, Liu mentioned that such efforts will involve high-capacity effusion cells, such as 10kg sources for indium and gallium.

One epiwafer technology that IQE is developing is that for dilute nitride lasers. Introducing this novel material allows an increase in the emission wavelength to around 1600 nm, for lasers lattice matched to either GaAs or germanium. Emitters in this spectral domain, in either the form of the VCSEL or the edge-emitter, could be deployed for sensing functions in smartphones, because emission is transparent to the OLED display. While MOCVD is the traditional workhorse for making GaAs-based lasers, particularly VCSELs, growth of the active region is found to be more successful by MBE.

IQE is active in the development of antimonide-based detectors on silicon substrates. Engineers have evaluated the quality of appropriate heterostructures on silicon, germanium-on-silicon templates and GaSb. While there are differences in defect density, values for quantum efficiency are similar. Supporting this finding is work with QmagiQ, a designer and manufacturer of infrared focal plane arrays for imaging. It has found that the performance is almost identical for all three types of substrate.

...and quantum-dot lasers

Delegates at ICMBE also got to hear from the Japanese firm QD Laser, a company with a tremendously strong pedigree in the production of quantum-dot lasers.

Speaking on behalf of this pioneer, company Technical Director Kenichi Nishi began his talk by acknowledging the significant contribution made to self-assembled quantum-dot lasers by one of the father's of MBE, Arthur Gossard, who passed away this July.

Nishi went on to list some of the key attributes of the quantum-dot laser: a low threshold current; low power consumption; minimal temperature sensitivity; high efficiency; a capability to operate at high temperatures; and tolerance to back reflection.

These attributes have motivated the development of this source, first proposed by Yasuhiko Arakawa and Horroyuki Sakaki from the University of Tokyo in 1982. Converting this idea into real devices came in the 1990s, led by the group of Nikolay Ledentsov, at the time at the A. F. Ioffe Physicotechnical Institute of Russian Academy of Sciences, but now CEO of VI Systems.

Another key milestone in the history of the quantum dot laser came in 2006, when Fujitsu span out Nishi's company, QD Laser, which makes quantum-dot lasers and other varieties of laser. According to Nishsi, the company's core technologies are: the GaAs-based epitaxy of quantum dots and quantum wells, the fabrication of gratings employing distributed Bragg reflectors, and chip testing. Products are manufactured using a standard solid-source Riber MBE 49 reactor, capable of accommodating up to five 75 mm GaAs substrates. Material from this tool is processed into quantum-dot lasers emitting at around 1.3 μm, and InGaAs quantum well lasers spanning 1000 - 1160 nm.

While MBE remains a great tool for producing samples for university research, it is also being used for academic efforts at developing real-word devices. Such efforts are sure to support tomorrow's high-volume manufacture of several devices by MBE within the compound semiconductor industry.

Nishi explained that the company's quantum-dot lasers are produced using the Stranski-Krastanov growth mode. Today's dots are typically around 20 nm in diameter, 7 nm high, and have a density of around 6 x 10^{10} cm^{-2}.

As the morphology of the quantum dots is very sensitive to pressure, temperature and growth rate, it is essential to eliminate fluctuations during production campaigns. Helping to do this is the decision to undertake maintenance on the reactor before it fails.

Over the years, engineers at QD Laser have refined the growth of their dots. Initially these nanostructures, with a density of around 3 x 10^{10} cm^{-2}, would produce a spectral peak with a width of about 35 meV and provide a gain of 25-30. Improvement first came from doubling dot density – this increased gain to 40-50. More recently, gain has been raised to 50-60 and the spectral width narrowed to around 25 meV, with refinements realised through optimised overgrowth and a suppression of diffusion, verified by bright-field transmission electron microscopy.

Since 2011, QD Laser has mass-produced lasers for optical communications, beginning with the shipment of Fabry-Pérot lasers. It has now shipped more than 4.5 million devices with a quantum-dot active region. For those lasers, temperature stability is very high, with no change in the eye diagram between 25 °C and 85 °C. Reliability is excellent, with no sudden deaths, while lifetime is estimated to be in excess of 300,000 hours. High-temperature operation is incredibly impressive, with quantum-dot Fabry-Pérot lasers capable of operation up to 220 °C and siblings with a distributed Bragg reflector able to produce single-mode lasing up to 150 °C.

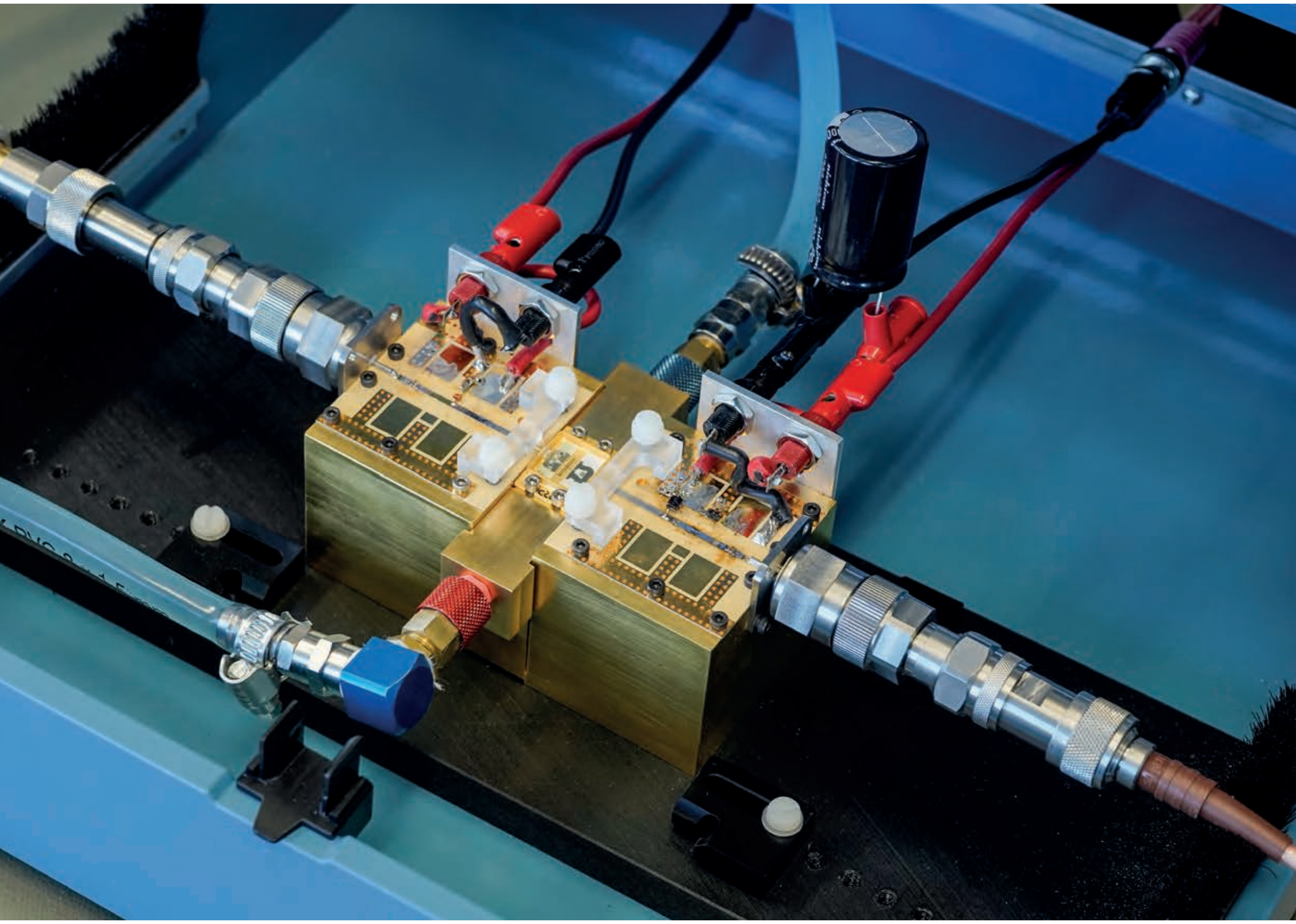
Nishi argued that one of the most promising applications for the quantum-dot laser is to provide a source for optical interconnects in data centres, where they can enable high-speed transmission with a small footprint. Additional opportunities include the light source for silicon photonics and lidar.

Helping to support an expansion in the number of quantum-dot sources is IQE, which is developing epiwafers for this class of laser. One option is growth on 150 mm GaAs wafers, an approach where this epiwafer provider has demonstrated a quantum dot density of 5 x 10^{10} cm^{-2}; it has also investigated the opportunity for fabrication on silicon substrates, which offer large wafer sizes, such as 300 mm, and CMOS compatibility.

According to Liu, the growth on III-V dots on silicon has seen "lots of progress" in the last few years. To drive further development, IQE has teamed up with John Bowers' group at the University of California, Santa Barbara. This collaboration, involving the production of heterostructures with a Veeco GEN2000 reactor, has led to the fabrication of lasers with a continuous-wave output power of 125 mW.

There are also efforts at improving the performance of quantum-dot lasers at the University of Kassel and University College London. Representatives of both groups spoke at the recent ICMBE conference, highlighting that while MBE remains a great tool for producing samples for university research, it is also being used for academic efforts at developing real-world devices. Such efforts are sure to support tomorrow's high-volume manufacture of several devices by MBE within the compound semiconductor industry.

➤ User group meetings were a feature of ICMBE. A jazz band played at Riber's evening, held at the student union building at the University of Sheffield. Credit: Laure Divisia.



Targeting the C-band with ultra-high-voltage HEMTs

GaN HEMTs with a minimal output capacitance and terminated harmonics deliver record-breaking powers and efficiencies

BY SEBASTIAN KRAUSE FROM THE FRAUNHOFER INSTITUTE FOR APPLIED SOLID STATE PHYSICS IAF

DURING THE LAST DECADE, the GaN-on-SiC material system has established itself as the dominating semiconductor technology for delivering very high powers in the gigahertz range. Its more established rival, silicon-LDMOS, is more popular, and the cheaper choice for powering most systems in the VHF and lower UHF spectrum. However, this incumbent is even losing market share in that application space to GaN: this wide bandgap rival is renowned for its higher device efficiency, which trims operational expenses; and its higher power per die area that enables the design of smaller and lighter systems.

The enviable position that GaN holds in the high-power market is primarily due to its capability to maintain a high efficiency, even at high voltages and hence high-power levels. In contrast, LDMOS struggles to find a sweet spot that ensures a good efficiency, alongside a high-power density and high-frequency performance. So usually a trade-off has to be made in device design, favouring one attribute. Or, to put it another way, GaN has the stamina to go the extra mile, in terms of its frequency range, while LDMOS is already running out of gas.

However, there's a need to understanding the underlying physical principles of these limitations, and pinpoint the critical device parameters that require careful tuning, in order to optimise GaN devices. Clearly, device scaling does not come for free.

Looking towards higher frequencies, the predominance of GaN is built on its capability to deliver very high powers and efficiencies. Yet, generally accepted scaling rules apply, implying that operation at higher frequencies must go hand-in-hand with a reduction in supply voltage. Consistent with this expectation are the product portfolios of manufacturers: they list the availability of 65 V devices up to 2 GHz, while those capable of 12 GHz and 18 GHz seem to mark the final frontier for 50 V and 40 V transistors, respectively. Beyond that, devices are rated for 28 V operation, if at all.

Last summer Integra Technologies of El Segundo, CA, launched a packaged 100 V GaN HEMT. This product pushes the boundaries for the supply voltage and ultimately the output-power-per-device. Designed for L-band avionics radar operating in the 1.030 GHz to 1.090 GHz band, this HEMT adheres to the mapped-out trend, highlighting once again that higher frequencies must be traded for supply voltage.

There are applications demanding kW-level powers higher in the spectrum, such as the C-band (4 GHz to 8 GHz) and even the X-band (8 GHz to 12 GHz). It makes much sense to try and address these opportunities with GaN, by taking on the challenge of marrying its high-frequency attributes with its outstanding high-power capabilities.

Keeping control of the charge

Unfortunately, when designers move to higher voltages, there is not much working in their favour. In fact, almost every critical performance parameter appears to get worse when raising the supply – there are problems associated with the transition frequency, greater trapping and diminished reliability to name but a few. All these issues stem from the rising electric field, which is the main factor to consider when trying to maintain performance when shifting operation to higher voltages.

Another major downside of a higher electric field is that it can lead to so-called 'short-channel effects'. When this happens the gate, which is solely responsible for controlling the electrons in the channel under ideal conditions, struggles to do its job. Short-channel effects tend to be associated with high-frequency technologies, because their occurrence usually leads to an 'under scaling' of electrical parameters – that is, electrical parameters scale less than what the scaling rules imply. Note that broadly speaking, scaling up in frequency or in

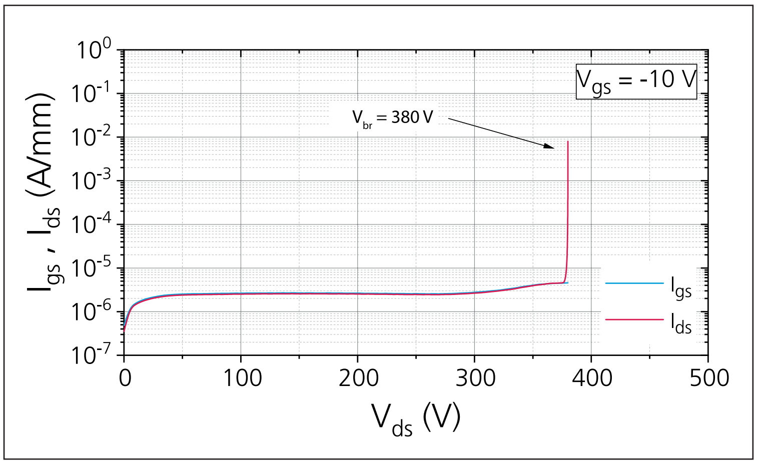


Figure 1. Drain-Source breakdown characteristics for a device with a total gate width of 1.2 mm (6 x 200 μm). For the measurement, the source of the device is grounded, whereas the gate potential is set to - 10 V. Then the drain potential is quickly raised until the recorded gate and drain current exceed the compliance value of 1 mA/mm, which is considered as breakdown.

voltage leads to similar field-related issues, unless appropriate countermeasures are taken.

One common countermeasure is to introduce field plates, a concept found in most GaN technologies up to Ka band. As its name suggests, the role of the field plate is to tame the electrical field by spreading this out from the gate towards the drain electrode. With its addition, there is a reduction in the maximum electric field close to the gate contact, and a quashing of short-channel effects. Another benefit is that a device can realise a higher breakdown voltage for a given on-resistance. Since a higher on-resistance translates to increased losses, it is crucial to keep this as low as possible when targeting the highest efficiency.

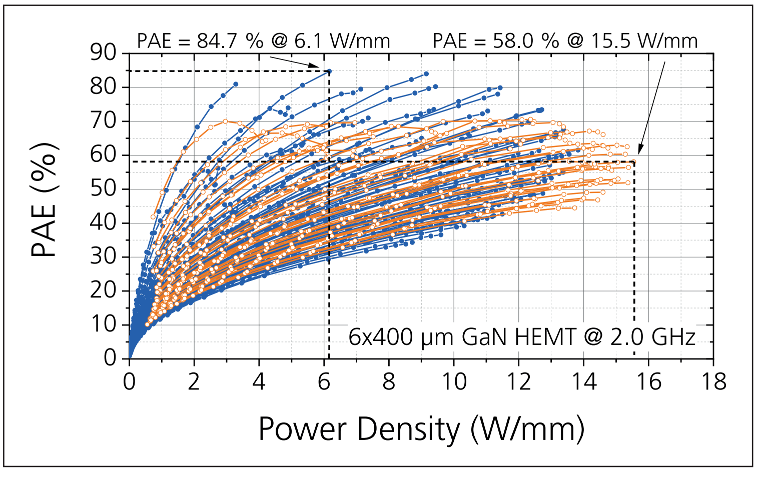


Figure 2. Pulsed load-pull measurements of a 100 V GaN HEMT with a total gate width of 2.4 mm (6 x 400 μm) at 2.0 GHz. The pulse width is 100 μs with a duty cycle of 10 percent. Two conditions are plotted here. Orange is for load pull at the fundamental frequency without termination of harmonics, while blue is for fundamental load pull with second harmonic impedances at input and output set for maximum efficiency.

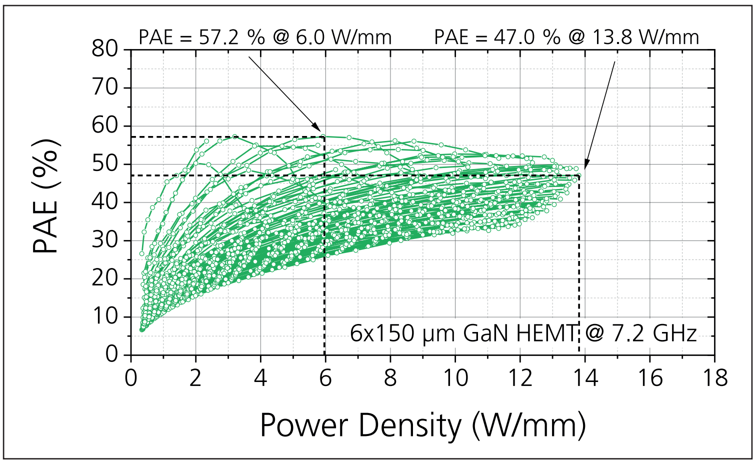


Figure 3. Pulsed load-pull measurements of a 100 V GaN HEMT with a total gate width of 0.9 mm (6x150 µm) at 7.2 GHz. The pulse width is 100 µs, with a duty cycle of 10 percent. No harmonics have been terminated during the measurement.

Working at the Fraunhofer Institute for Applied Solid State Physics IAF, our team is engineering devices to try and meet these criteria. Measurements show that the breakdown voltage for our 100 V GaN HEMTs is in excess of 350 V (see Figure 1). Meanwhile, on-resistance is just 4.2 Ω mm, a value merely one-third higher than that of established 50 V GaN processes.

Setting the stage for harmonics

At first glance, it would appear to be rather conservative to have such a high breakdown voltage for a 100 V device. However, there is good reason behind this caution – harmonic termination. When you dive a bit deeper into high-efficiency amplifier design, you are very likely to come across this technique of manipulating harmonic impedances.

Ultimately limiting the efficiency of an ideal amplifier is its class of operation. While class A and class B are probably familiar to most of us, brave designers opt for class E, class F or class F^{-1}, which is also known as inverse class F. These latter three have a theoretical efficiency of 100 percent, while class B and class A are limited to 78.5 percent and 50 percent, respectively. In practice, all these numbers are impossible to achieve, due to the lossy nature of real devices. However, efficiencies as high as 90 percent have been demonstrated for GaN HEMTs. I doubt you expected a free lunch, so you'll not be surprised that harmonic termination comes at a cost. Presenting specific impedances to the device at its harmonic frequencies – ideally a short or open circuit – alters the time domain waveform at the device output. For Class E and class F^{-1}, there can be waveforms with a voltage magnitude as high as three-and-a-half times the supply voltage. Such a high voltage arises due to the high second harmonic impedance (at or close to an open circuit) that is required for the operation modes. Due to this, a sufficiently high breakdown voltage is a pre-requisite for reaching the highest efficiency levels.

At higher frequencies the concept of harmonic termination slowly falls apart. This arises because real devices show a finite output capacitance in parallel to the intrinsic current source. Over frequency the reactance of the output capacitance decreases, forming a shunt current path to ground. If the designer now tries to force the device into class-E or class-F^{-1} operation, the open circuit at the second harmonic is bypassed by the output capacitance. At a certain frequency this results in an effective short-circuit for the second harmonic and all higher harmonics. This set of shorted harmonic impedances leads to the class-B condition, limiting the maximum theoretical efficiency from 100 percent to 78.5 percent.

In addition to this road block to realizing a high efficiency at high frequencies, there is another issue associated with high voltages. In this case it is the praised field plates that are part of the problem. Most troublesome are the so-called source-terminated field plates – they can account for a large proportion of a device's output capacitance. It's tempting to simply ban this form of field plate from the device layout, but such a move would contradict the goal of proper field control. Like many times in life, it's better to seek a good trade off.

Stepping up in efficiency

Previously, we demonstrated a power-added efficiency of more than 77 percent at 1.0 GHz, a record for 100 V GaN HEMTs at the time. However, we uncovered some weak spots when we compared this device to our baseline 50 V devices. Deficiencies included a maximum efficiency that lagged the baseline devices by around 7 percentage

> We believe that more is possible. There is no reason to think that the C-band is the ultimate limit for 100 V GaN HEMTs. Our high levels of performance at these frequencies imply that there is still room to push the technology towards the X-band.

points. We also observed a pronounced efficiency roll off when measuring our 100 V devices at higher frequencies.

To address these weaknesses, we decided to make a fresh start. This involved redesigning the epitaxial stack and the intrinsic device features, with the goal of tightening the electrostatics. When we extracted the drain-induced barrier lowering – a measure that quantifies the parasitic control over the electrons by the drain contact, with the lower the value the better – we verified our success. This key figure of merit showed a five-fold reduction, yielding a value below 1 mV/V. In a nutshell, this result reveals that the gate has all the power over the electrons, without any interference from the drain at high voltages.

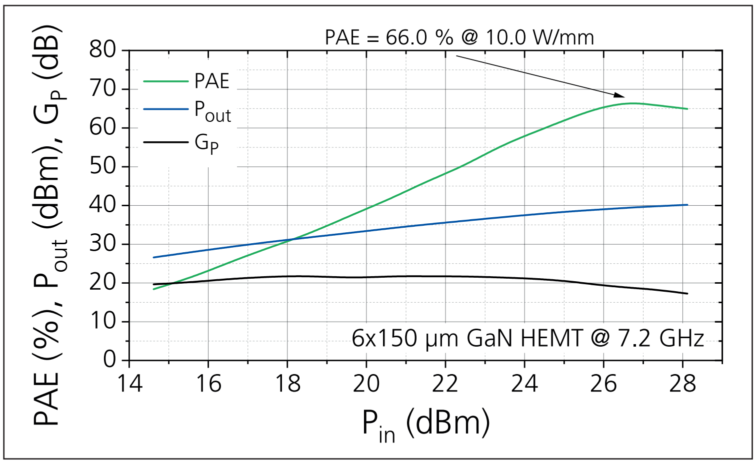
Further measurements underscored the capability of this new device. They revealed a record-breaking power-added efficiency for our 100 V GaN HEMT at 2.0 GHz of 84.7 percent – that's an increase of almost 8 percentage points, despite a doubling in frequency. The maximum power density hit 15.5 W/mm (see Figure 2).

There's more to our second-generation device than just headline-grabbing figures. By revising the intrinsic device layout, we have shaved off as much of the output capacitance as possible without deteriorating electrostatics. This refinement should enable these transistors to operate efficiently at much higher frequencies than before. By trimming the output capacitance by 40 percent, theory would suggest that these devices are susceptible to harmonic termination at higher frequencies.

Evidence from the lab supports this view. Measurements at the upper C-band frequency of 7.2 GHz – used by the European Space Agency for Deep Space Antennas to track spacecraft throughout the complete solar system – provide very impressive results. According to fundamental load-pull measurements, the power density is only a little down from the value for 2.0 GHz, reaching an impressive 13.8 W/mm. Meanwhile, power-added efficiency tops out at 57.2 percent.

Still, the question remained on whether terminating harmonic impedances would enhance efficiency. Due to set-up limitations, we could not tune the input and output simultaneously, as we had done for the 2.0 GHz measurement. So we tuned just the output second harmonic, and selected a fundamental load that provided a judicious combination of efficiency and power density. We then optimized the second harmonic phase, until we found the setting that yielded the maximum efficiency (see Figure 4 for the results of the power sweep).

The reduction in the output capacitance has paid off. The power-added efficiency has climbed to 66.0 percent, an increase of around 9 percentage points compared with the load pull without second



➤ Figure 4. Pulsed load-pull measurements of a 100 V GaN HEMT with a total gate width of 0.9 mm (6 x 150 μm) at 7.2 GHz. The pulse width is 100 μs, with a duty cycle of 10 percent. For this measurement a 'trade-off' of fundamental impedance was chosen that yielded a good combination of efficiency and power density. Additionally, the second harmonic at the output of the device was set for the value that showed the highest power-added efficiency.

harmonic termination. This value also sets a new benchmark for the efficiency of 100 V GaN HEMTs in the C-band. No less impressive are the associated power density of 10 W/mm and the gain of 18.5 dB, both achieved at the maximum power-added efficiency. Crucially, these performance numbers are realized simultaneously, rather than marking the individually best obtainable values – that sets these 100 V devices apart from commercially available GaN technologies. While the power-added efficiency of our ground-breaking HEMTs is comparable to the best 40 V and 50 V technologies, the power density and gain of our 100 V devices is a big step up from the capabilities of today's commercially available GaN HEMTs.

We believe that more is possible. There is no reason to think that the C-band is the ultimate limit for 100 V GaN HEMTs. Our high levels of performance at these frequencies imply that there is still room to push the technology towards the X-band. We don't know where exactly the frequency limitations of these high-voltage devices are, but we are prepared and willing to find out.

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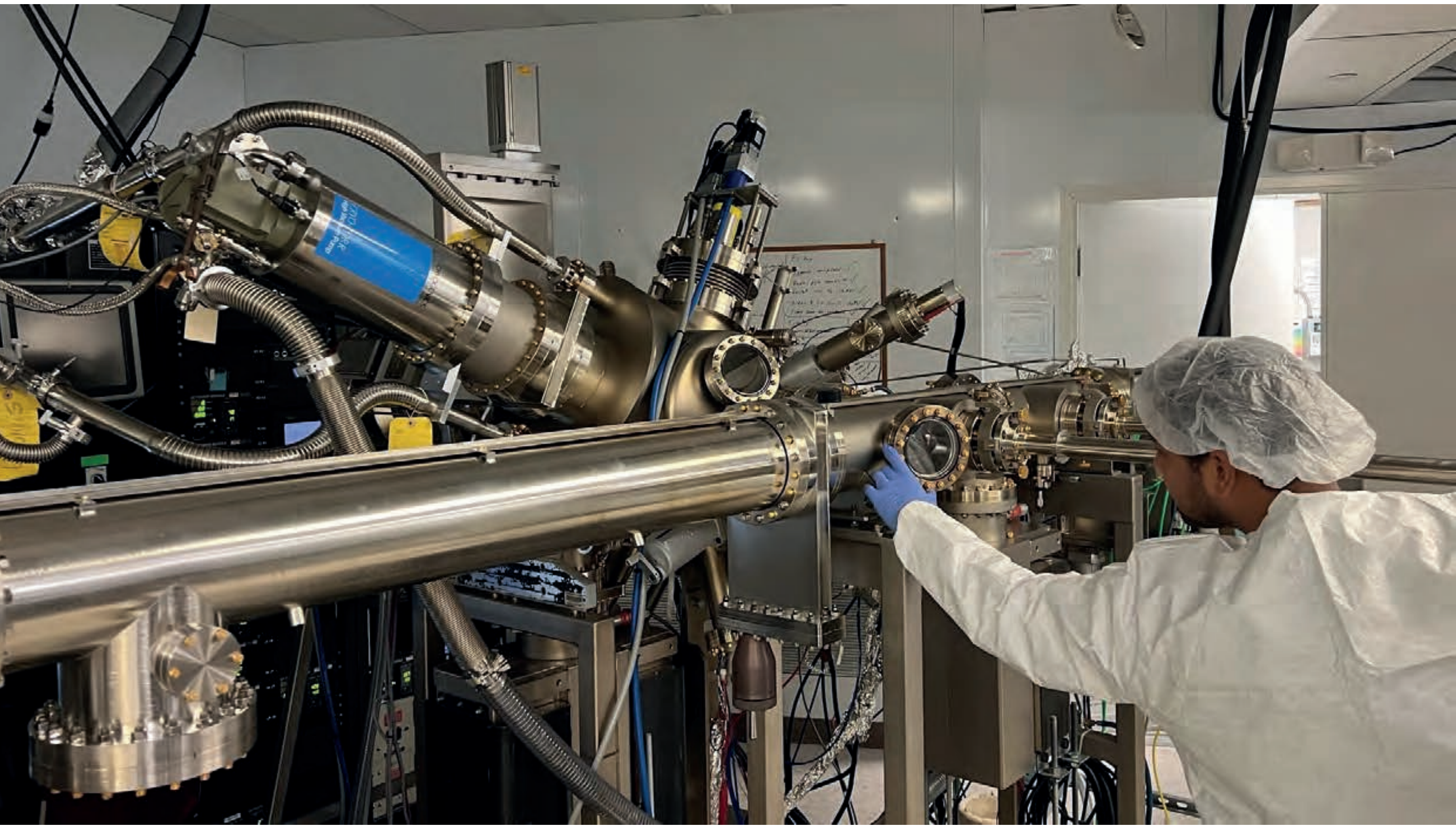


Reverse polarization invigorates the green LED

Switching to a *p*-down architecture produces a near-theoretical operating voltage for the green LED

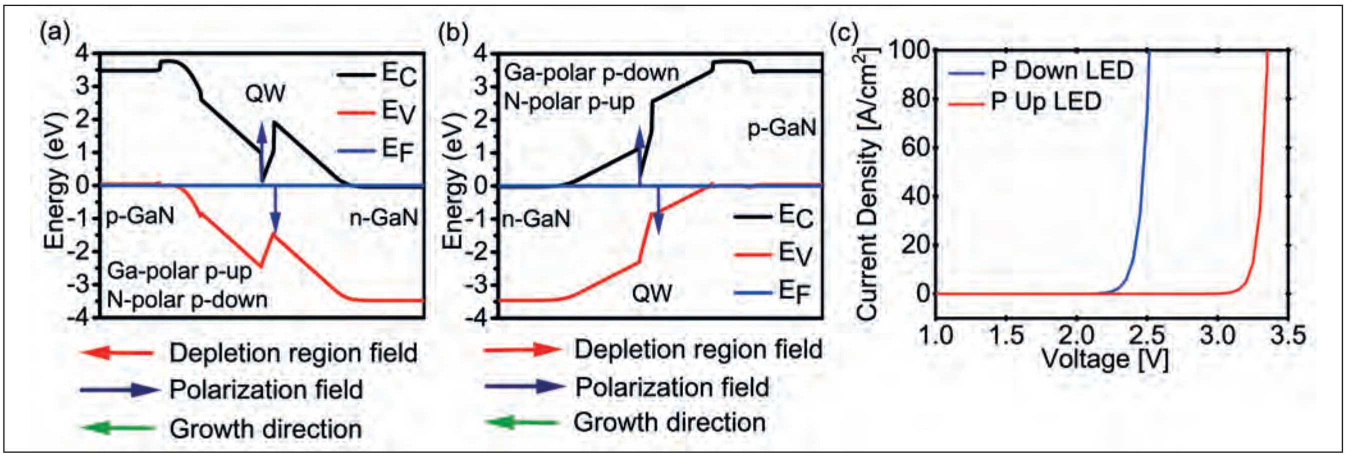
BY SHEIKH IFATUR RAHMAN, ZANE JAMAL EDDINE, AGNES XAVIER AND SIDDHARTH RAJAN FROM OHIO STATE UNIVERSITY AND ROB ARMITAGE FROM LUMILEDS

The GaN-based LED has come an awfully long way since its invention in 1989. Initially emitting blue light, then white once combined with a phosphor, this device enjoyed its first killer application from backlighting the keypads and screens of mobile phones. Further success followed with the backlighting of larger screens, found on TVs, laptops and tablets; and today sales are even more substantial, thanks to the deployment of this device in general illumination, transport and horticulture. And that may not be the end of the line, as this device is now showing promise in microLED displays.

Yet despite all this great and varied success, there are weaknesses that need to be addressed. While the efficiency of emitters in the violet and blue is now exceptional, the value for this key figure of merit plummets at longer wavelengths. The issue is that when engineers stretch the emission wavelength to 500 nm or more by increasing the indium mole-fraction of the InGaN quantum wells, they come up against several challenges, all contributing to degradation in device performance and a decline in wall-plug efficiency.

How does polarization impact LEDs?

InN, GaN, and AlN are all examples of group III-nitride wurtzite materials that are pyroelectric and display spontaneous and piezoelectric polarization. Due to these characteristics, heterostructures formed from different alloy compositions of



➤ Figure 1. (a), (b) Equilibrium band diagram of *p*-up and *p*-down configuration showing a low hole-injection barrier for a *p*-down design compared with a *p*-up variant; and a higher in-built electron barrier for *p*-down, improving confinement of electrons in the quantum well compared to *p*-up. (c) Simulated current density versus voltage (J-V) curve for the *p*-up and *p*-down LED structures.

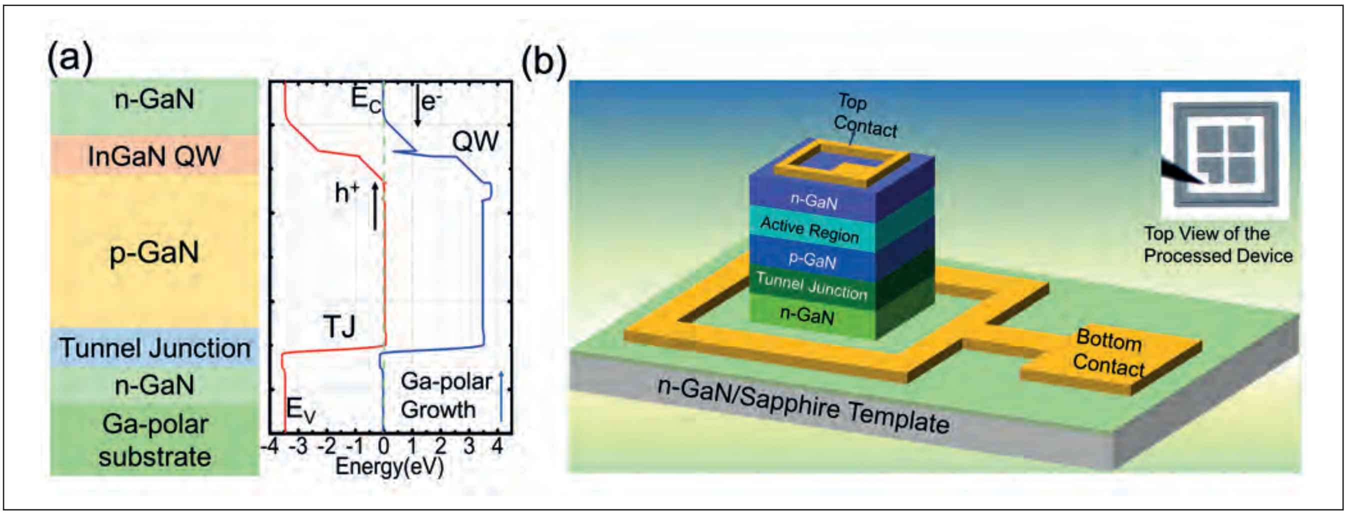
III-nitrides have inherently large spontaneous and piezoelectric polarization sheet dipoles at their interfaces. When these materials form thin sandwich-like layers, such as quantum wells, this results in large electric fields within the wells, and depletion regions outside the wells.

To emit at wavelengths beyond 500 nm, the cusp of the green spectral domain, the average indium composition in the quantum well must exceed 20 percent. Adding this much indium or more pays the penalty of an increased electric field strength within the quantum wells, influencing the distribution and lifetime of free carriers in these light-emitting layers. Higher fields can diminish the performance of InGaN/GaN-based optoelectronic devices and increase their operating voltage.

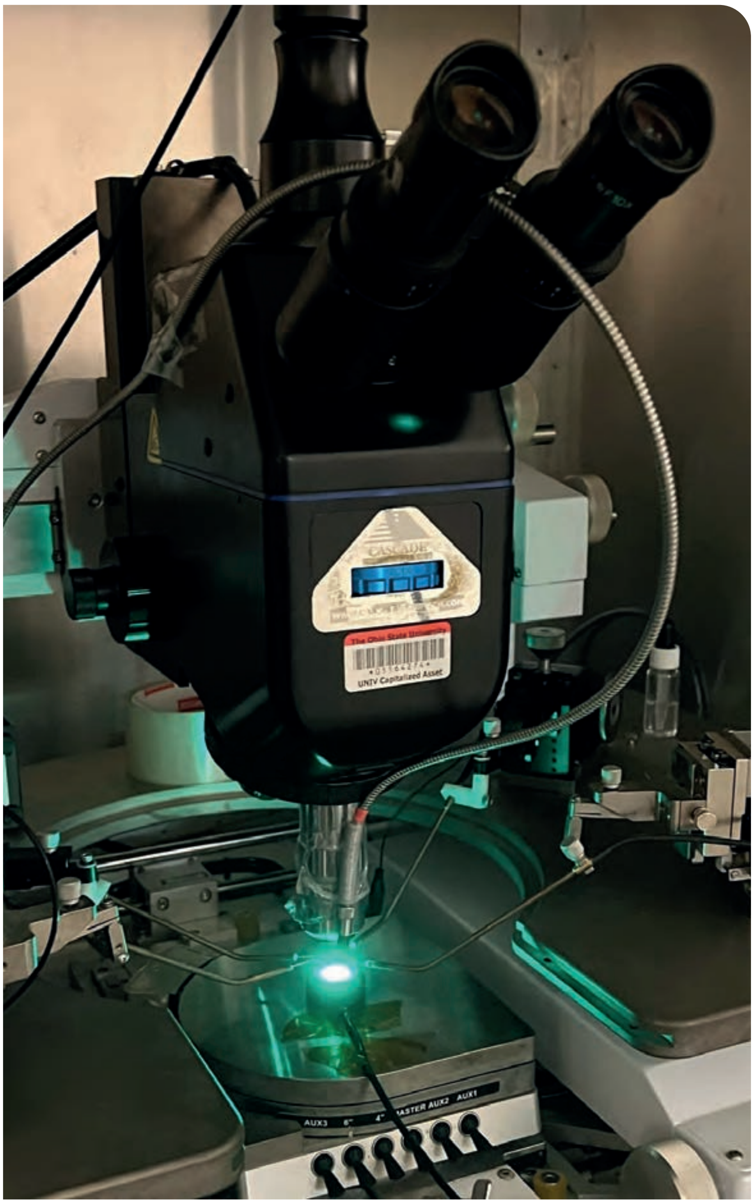
In conventional LEDs, formed by growing the *n*-type region first, followed by the active region and then the *p*-type region – such structures may be known as simply *p*-up LEDs – the polarization sheet charges oppose the depletion region field across the *p*-*n* junction. This leads to higher electrostatic barriers that impede the injection of electrons and holes, and ultimately a higher forward-voltage drop (see Figure 1 (a)).

One interesting alternative architecture is formed by reversing the relative direction of the *p*-*n* junction. This is realized by placing the *p*-layer below the active region, rather than above it. With this geometry, the polarization field no longer opposes the depletion barrier field. Instead, these aligned fields are beneficial, helping to lower injection barriers for electrons and holes into the active region (see Figure 1 (b)).

For the indium-rich wells needed to realize longer-wavelength emission, such as the green, this carrier-assisting effect is particularly strong. According to simulations, there is a significant reduction



➤ Figure 2. (a) Equilibrium band diagram of the *p*-down LED using a bottom tunnel junction. (b) The finished/processed device.



➤ On-wafer LED measurement set up.

in the injection barrier, leading to a tremendous reduction in the forward turn-on voltage for *p*-down LEDs compared with their traditional cousins (see Figure 1 (c)).

Why do we need tunnel junctions?

There are two options for reversing the relative orientations of the *p-n* junction and polarization. One is to maintain the conventional *p*-up architecture, but to switch substrate and grow along the –*c* or N-polar direction of the wurtzite crystal structure. The alternative is to grow a *p-n* junction with the *p*-type region below the active region, along the +*c* or Ga-polar direction.

Our collaboration between Ohio State University and Lumileds has been evaluating these approaches for many years. In 2012 we broke new ground, providing the first demonstration of the N-polar green LED. This work illustrated the benefits of reversed polarization, such as a lower turn-on voltage and a reduced overflow. But we found that the N-polar orientation is not a panacea – it can introduce challenges associated with a higher point defect incorporation, which diminishes the internal quantum efficiency.

It is preferable to produce LEDs with the same sense of polarization as the *p-n* diode, but with growth along the Ga-polar direction. For this particular design, the concern is that since the *p*-layer is at the bottom, the spreading resistance of the *p*-layer could lead to current crowding.

A team from Cornell has tackled this issue by inserting a tunnel junction below the *p*-layer. However, operating voltages for these *p*-down green LEDs were significantly higher than those of conventional variants.

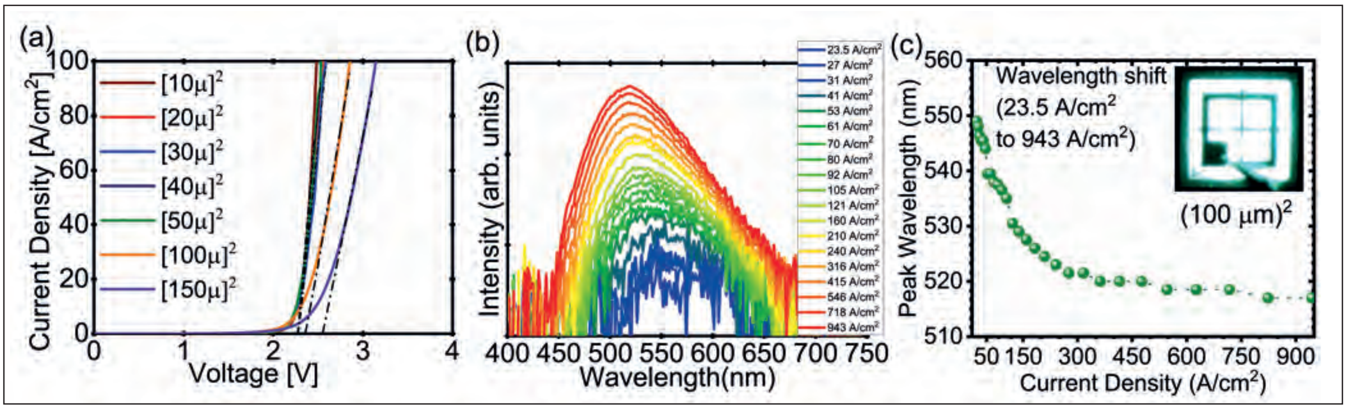
We have had more success with this approach. This has led us to show, for the first time, that highly efficient tunnel junctions can be integrated within *p*-down LEDs to yield green-emitting sources with an extremely low operating voltage.

How did we demonstrate the result?

Fabrication of our novel LEDs began with the growth of an epitaxial structure by plasma-assisted MBE (see Figure 2). We prefer this growth technology to MOCVD for our novel LEDs: it enables the sharp doping profile and the high magnesium and silicon doping densities that are essential for good homojunction tunnel junctions.

Our on-wafer measurements clearly show the benefit of reversed polarization. When driven at current densities of 20 A cm^{-2} and 100 A cm^{-2}, the forward voltages for our LEDs are just 2.42 V and 2.75 V, respectively (see Figure 3 for a plot of the

We believe that this reduction to the operating voltage will have significant impact on future display and lighting applications employing longer wavelength emitters. What's more, the switch to an *n*-type region above the LED could unleash several benefits associated with higher-level integration of other electronic devices, such as Schottky diodes and transistors.



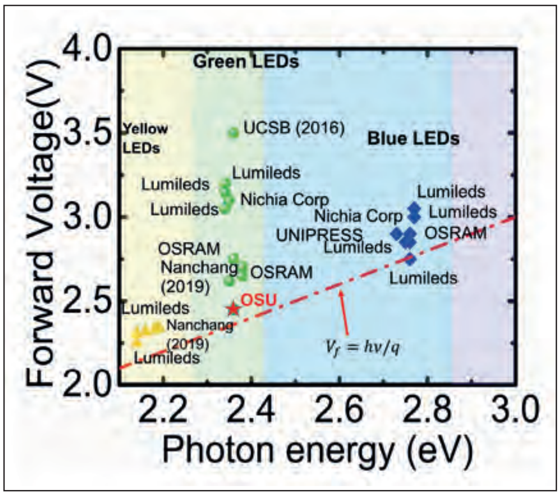
➤ Figure 3. (a) Electrical characteristics of *p*-down tunnel-junction (TJ) LEDs with different device areas (linear scale). The fitted lines (in black) used to extract the turn-on voltage are shown in the linear plot. (b) On-wafer electroluminescence spectra of a TJ-LED at a low current density to high current densities. (c) Electroluminescence peak shift plot showing the peak shift for current densities from 23 A cm^{-2} to 943 A cm^{-2}. Inset of (c) shows an optical micrograph of the device under operation.

dependence of current density on voltage for these devices).

At the lowest current density where emission can be detected (23 A cm^{-2}), peak electroluminescence is 548 nm, corresponding to a photon energy of 2.27 eV. As current density increases, emission shifts to 518 nm due to band filling and polarization charge screening.

To analyze voltage loss due to injection, we have plotted the operating voltage as a function of photon energy. This shows that our LEDs have operating voltages very close to their photon energies. When we compare this observation to previous accounts of green LEDs in the literature (see Figure 4), we find that our values are significantly lower than those previously reported. We therefore conclude that the lowered barriers from the reversed polarization deliver a significant reduction in the turn-on voltage.

While the absolute external quantum efficiency of our LEDs is low, likely due to the impact of MBE growth conditions on the internal quantum efficiency of the wells, our work is still an important breakthrough – the measurements of the voltage drop provide convincing proof that the introduction of a reverse polarity *p*-down architecture improves the injection of carriers into an LED, and thereby reduces its operating voltage. We believe that this reduction to the operating voltage will have significant impact on future display and lighting applications employing longer wavelength emitters. What's more, the switch to an *n*-type region above the LED could unleash several benefits associated with higher-level integration of other electronic devices, such as Schottky diodes and transistors. We view our design and demonstration of efficient tunneling-based, *p*-down LEDs as providing a framework for exploring other designs, including longer-wavelength LEDs and novel, multiple-active-region LEDs.



➤ Figure 4. Benchmark plot showing the forward-voltage drop at 20 A cm^{-2} or 35 A cm^{-2} for III-nitride LEDs from blue to yellow. The red line represents the lowest theoretical voltage drop, $V_f = h\nu$, where $h\nu$ is the photon energy and V_f is the forward voltage.

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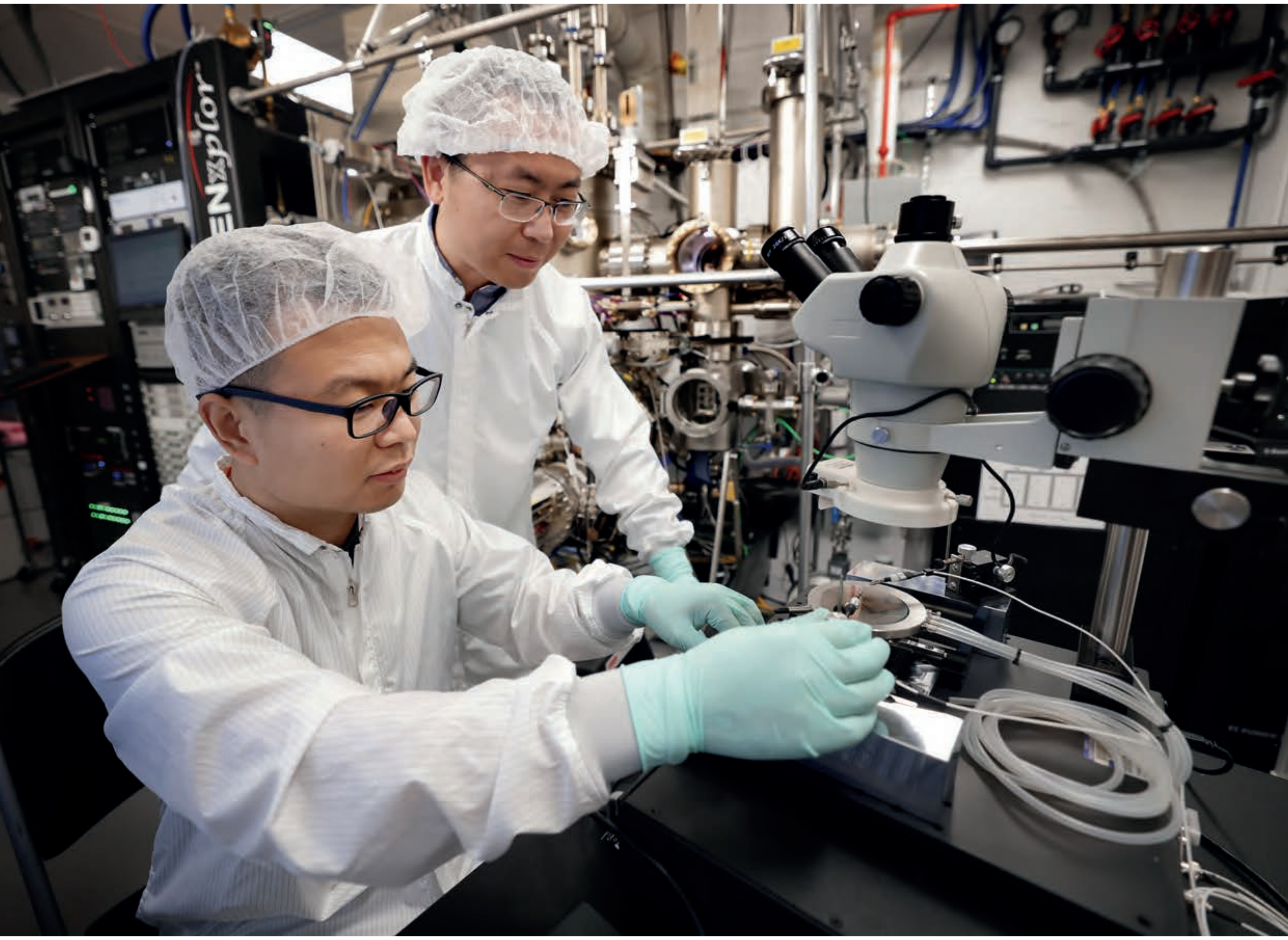


A game changer: Epitaxially grown nitride ferroelectrics

Precisely tuning electrical polarization switching of nitride semiconductors provides a pivotal step towards next-generation electronics

BY PING WANG, DING WANG AND ZETIAN MI FROM THE UNIVERSITY OF MICHIGAN

Ferroelectrics have a big part to play in tomorrow's world. They are critical to the development of next-generation electronic, optoelectronic, acoustic and quantum devices. The desired characteristics are a high Curie temperature, a large electromechanical response, a large remnant polarization, a wide range tuneable operating voltage, a high crystalline quality and a compatibility with mainstream semiconductor technology. Ferroelectric materials with all those attributes can produce transistors, memristors, sensors, actuators, quantum switches and transducers operating at high powers, high frequencies, high efficiencies and high-speed, while drawing very little power.

Over the last few decades there has been significant advancement in the theoretical models, material

Left: Ferroelectricity testing of MBE-grown ScAlN films. (Photo by Brenda Ahearn)

synthesis and characterization of ferroelectrics. A key milestone came in 2011, with the discovery of ferroelectricity in doped HfO_2. Since then, ferroelectrics have been taken more seriously, and have been integrated into some mainstream semiconductor manufacturing processes. However, the commercialization of HfO_2-based devices has been held back by challenges associated with ferroelectric phase stability, an imprint issue, the wake-up effect and a high coercive field.

One promising class of piezoelectric material that is well known to all of us is AlN-based nitride semiconductors. They exhibit a strong spontaneous polarization along the *c*-axis, leading to two stable lattice states – metal-polar and nitrogen (N)-polar – with opposite polarization. In principle, these two states are electrically switchable via an intermediate metastable hexagonal phase. Unfortunately, due to the giant energy barrier between the wurtzite and hexagonal phases, this transition cannot happen without causing dielectric breakdown.

Despite this drawback, the spark of interest has not been extinguished. Twenty years ago, working independently, researchers in the US and Mexico predicted the existence of wurtzite-phase, scandium-based III-nitrides (Sc-III-N) with a distorted lattice. These calculations indicate that there is a chance to reduce the polarization switching energy barrier. Detailed theoretical studies have strengthened the case, but there is yet to be much experimental progress.

Realising ferroelectricity in nitride semiconductors is expected to unleash a significant revolution on the research of not only third-generation wide bandgap semiconductors, such as GaN, SiC and AlN, but also on ferroelectric materials in general. Spurred on by the abnormal enhancement of the piezoelectric response observed in ScAlN alloys by a team from the National Institute of Advanced Industrial Science and Technology, Japan, in 2009, much effort has been directed at exploring this alloy as the first candidate for providing ferroelectricity in nitride semiconductors.

In 2019 a German collaboration between the University of Kiel and the Fraunhofer Institute for Silicon Technology reported significant progress in ScAlN ferroelectrics. This partnership demonstrated ferroelectric polarization switching in sputtered polycrystalline ScAlN films, which possess a remnant polarization in excess of 100 $\mu C\ cm^{-2}$ and a paraelectric transition temperature in excess of 600 °C.

Motivated by this success, funding programmes emerged almost immediately in several countries to support further research. From that point on, it's been a race to see who could grow this class of ferroelectric semiconductors with a process that's compatible with mainstream semiconductor technologies.

A fundamental building block to fulfilling this goal is the epitaxial growth of nitride ferroelectrics. MOCVD and MBE are obvious options, given their success in high-throughput growth of many III-nitride device structures, such as LEDs, laser diodes and HEMTs. However, the growth of Sc-III-N by either MOCVD or MBE is extremely challenging. Efforts have been underway since the turn of the millennium, with early studies tending to focus on the addition of scandium into GaN, due to the tuneable bandgap of ScGaN in the visible domain. Highlights include a report from Ohio University of wurtzite-like growth of a ScGaN alloy by MBE in 2004, and the finding

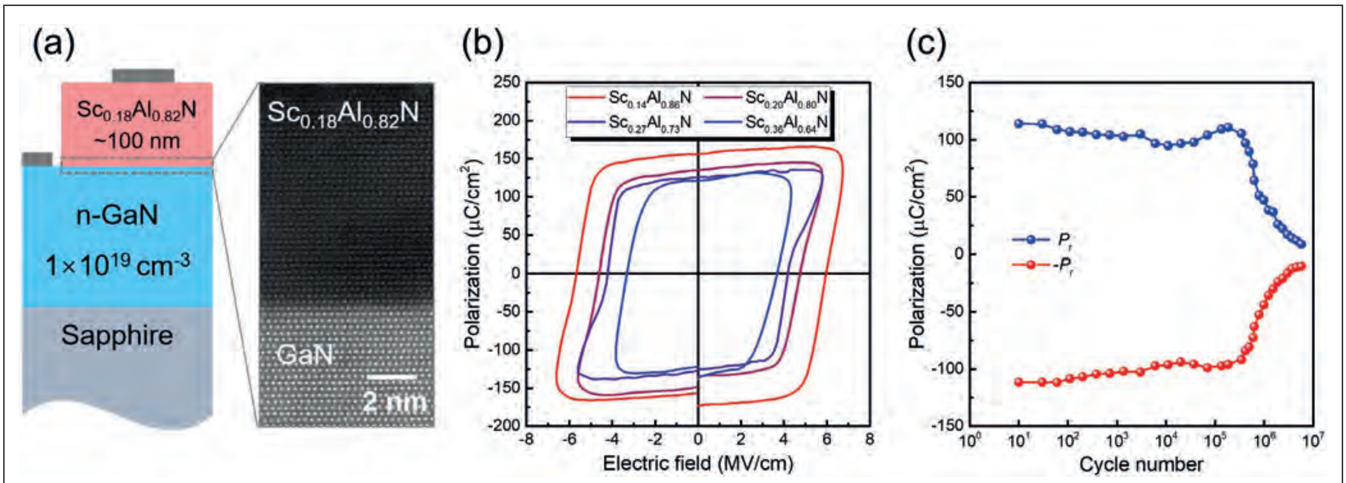
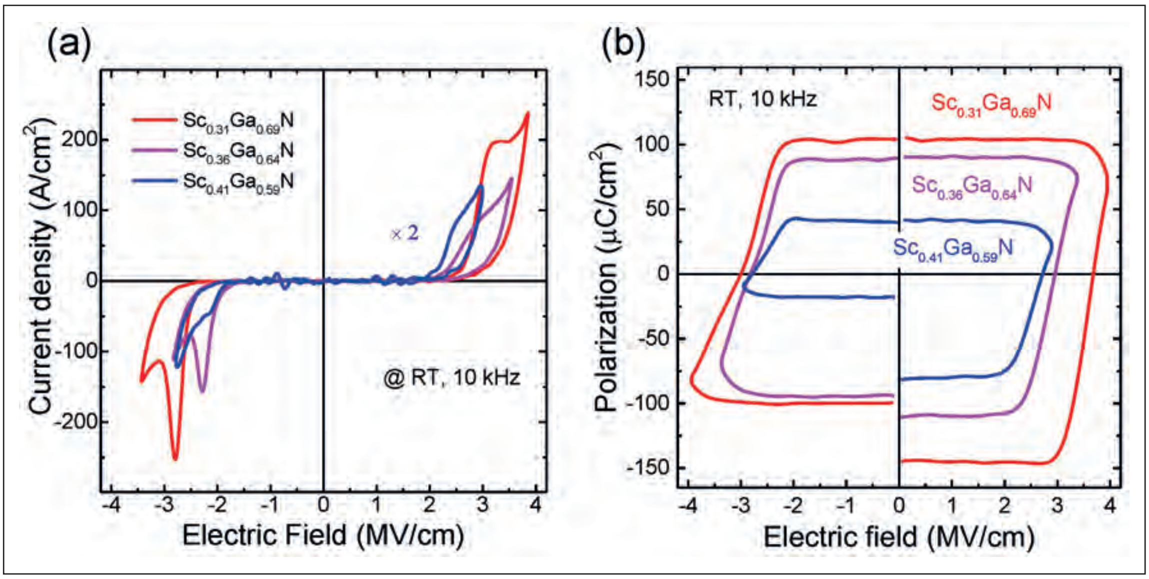


Figure 1. (a) Diagram and scanning tunnelling electron microscopy image of the ScAlN/GaN interface. Taken from D. Wang *et al.* Adv. Electron. Mater. **8** 2200005 (2022). (b) Polarization-electric-field loops measured at 40 kHz for ferroelectric ScAlN with varying scandium content. (c) Remnant polarization during the endurance test for $Sc_{0.20}Al_{0.80}N$ using 10 μs pulse width. Taken from P. Wang *et al.* Appl. Phys. Lett. **118** 223504 (2021)



➤ Figure 2. (a) Loops of current density as a function of electric field at 10 kHz for ScGaN films with varying scandium content. (b) Loops of polarisation as a function of electric field, extracted from a set of unipolar triangular waveform sequences with a frequency of 10 kHz. Taken from D. Wang *et al.* Appl. Phys. Lett. **119** 111902 (2021).

by a team from Sandia National Laboratories of the incorporation of scandium in GaN at the doping level, realised by MOCVD and announced in 2009.

Due to a complicated phase diagram, epitaxial growth of crystalline ScAlN is more elusive than its ScGaN cousin. This challenge explains why the experimental growth of the later has only recently been reported. Initial success came from a team from the Naval Research Laboratory, reporting MBE growth of wurtzite phase ScAlN films in 2017. A German collaboration between the Fraunhofer Institute for Applied Solid State Physics IAF and INATECH – Albert-Ludwigs University Freiburg has claimed similar success, using an upgraded MOCVD system.

While these milestones are important, they did not ensure the demonstration of ferroelectricity in ScAlN. For that crucial breakthrough, success has recently come from our team at the University of Michigan. To succeed in that endeavour, we had to increase the breakdown field beyond the polarization switching field – that is, the coercive field. This move is critical to overcoming the switching energy barrier between metal-polar and N-polar lattice states.

For this work we selected MBE. It is an excellent technique for epitaxy of nitride semiconductors in an ultra-high vacuum environment, thanks to its high controllability of impurities, doping levels, interfaces, domain structure, lattice-polarity and so on. Crucially, it can enable full integration of nitride ferroelectrics with workhorse GaN and silicon technologies, as well as thickness scaling down to a single atomic layer.

The significant advantages of MBE over other epitaxial techniques has led our team to conduct several systematic investigations that span material growth to the demonstration of ferroelectricity and the development of a broad range of devices. Over the years we have accumulated rich experience surrounding the control of phase purity, crystal quality, impurity incorporation, interface quality and lattice-polarity. This expertise has provided a great foundation for realizing ferroelectricity in epitaxial, single-crystalline ScAlN films.

High-quality material is at the heart of fundamental material studies and practical device applications. Thanks to the tremendous freedom offered by a versatile MBE system, we can readily explore and optimize conditions for depositing single-crystalline, wurtzite-phase ScAlN with high crystal quality, atomically sharp interfaces, a high breakdown field and a controllable scandium content (see Figure 1 (a)).

We have passed many milestones on our road to realising epitaxially grown ferroelectric ScAlN and related devices. To establish the possibility of integration and maximize the potential applications for ferroelectric ScAlN with GaN architectures, we have focused primarily on ferroelectricity in polar ScAlN/GaN heterostructures.

MBE-grown ferroelectric ScAlN

When we increased the breakdown field in our MBE-grown ScAlN films beyond the electric field that is needed for polarization switching, we observed the first ever clear box-like hysteresis polarization over electric field loops. This finding, seen in ScAlN films with various scandium compositions (see Figure 1 (b)), offers strong evidence for ferroelectricity. Strengthening the case are detailed electrical measurements and piezoresponse force microscopy studies.

If ferroelectric ScAlN is to serve in practical device applications, it must be stable and reliable. Initial results have been very encouraging, with electrical poling in our MBE-grown ScAlN films presenting a polarization retention time beyond 10^5 s, with negligible degradation in 10 years. Our endurance tests uncover no obvious fatigue, with up to 10^5 times bipolar electrical cycling (see Figure 1 (c)).

Recently, we have obtained even more impressive results, including an increase in the endurance strength beyond 10^7 cycles. With further studies and optimization, we are confident that reliability during electrical cycling for ScAlN will surpass that of the commonly studied HZO and PZT ferroelectrics.

As part of this investigation, we have demonstrated fully epitaxial ferroelectric ScAlN/GaN heterostructure memristors. These devices show stable operation at a high temperature of 670 K, which is close to or even above the Curie temperature of most conventional ferroelectrics.

MBE-grown ferroelectric ScGaN

Polarization is what makes III-nitrides unique. This opportunity to control and switch the polarization opens up new applications in memory, reconfigurable power devices and piezo devices, as well as quantum photonic devices with unprecedented stability, performance and functionality.

With this goal in mind, we have turned our attention to a related but less explored class of material, ScGaN, which has been shown to have a level of ferroelectricity similar to ScAlN. However, prior to our work there has been an absence of experimental demonstration of ferroelectric ScGaN, produced by either sputtering or epitaxial growth.

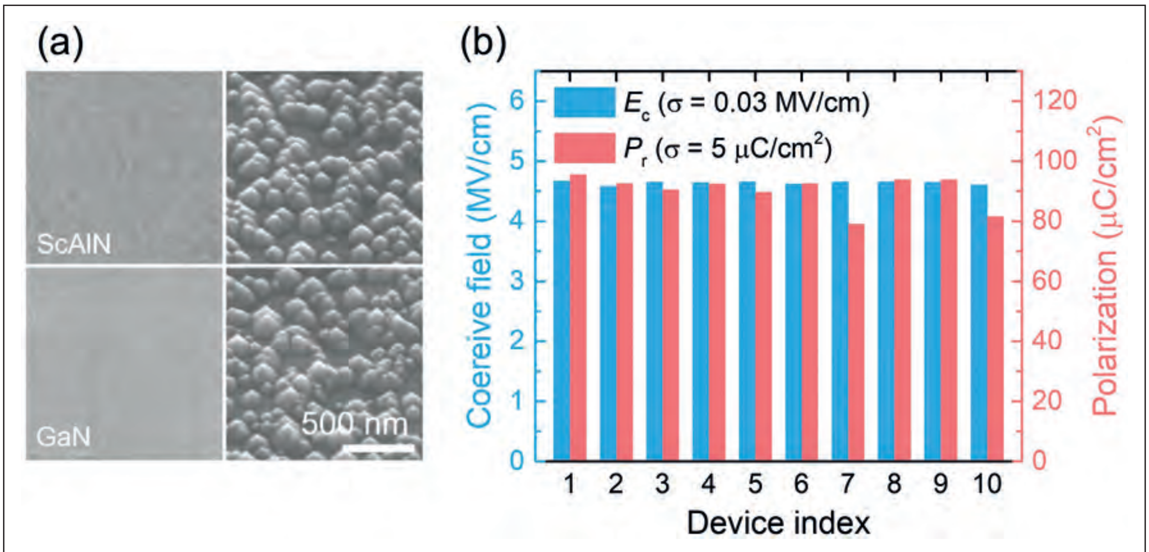
We have formed wurtzite ScGaN films on GaN by MBE, using similar growth strategies that we used to produce epitaxial ScAlN. By carefully adjusting the scandium composition we have discovered a narrow window where ferroelectric ScGaN is accomplished and lattice-polarity electrically switched (see Figure 2). Following our study, researchers from the National Institute of Advanced Industrial Science and Technology in Japan have also reported ferroelectricity in sputtered ScGaN films.

Polarization is what makes III-nitrides unique. This opportunity to control and switch the polarization opens up new applications in memory, reconfigurable power devices and piezo devices, as well as quantum photonic devices with unprecedented stability, performance and functionality

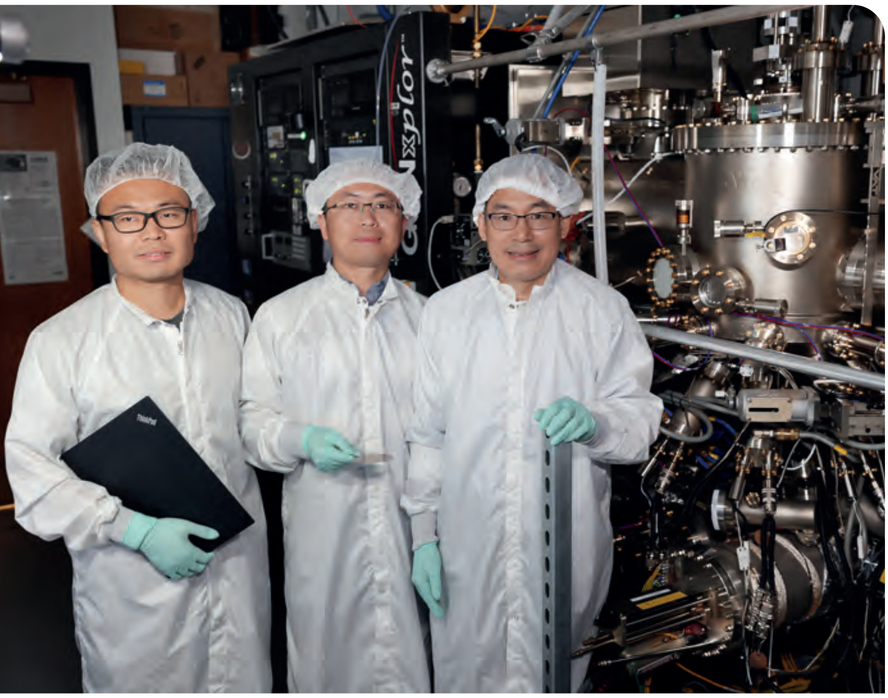
Given the widely tunable bandgap between AlN and GaN, realising ferroelectricity in fully epitaxial ScAlN and ScGaN promises to provide a unique material platform with an unprecedentedly tuneable lattice, bandgap, polarization, and ferroelectricity.

N-polar ferroelectric ScAlN

One of the most promising applications for ScAlN is as the barrier layer in a GaN-based HEMT.



➤ Figure 3. (a) Scanning electron microscopy (SEM) images of as-grown (left panel) and wet chemical etched (10 wt. TMAH at 50 °C for 5 min, right panel) surface morphology for an N-polar ScAlN epilayer (upper panel) and a GaN buffer (lower panel). All SEM images share the same scale bar. (b) Coercive field and remnant polarization measured in 10 randomly distributed ferroelectric N-polar ScAlN/GaN capacitors. Taken from P. Wang *et al*. Appl. Phys. Lett. **121** 023501 (2022).



➤ Sc-III-N research at the University of Michigan. From left to right: Dr. Ding Wang, Dr. Ping Wang, and Prof. Zetian Mi. (Photo by Brenda Ahearn)

Analogous to AlGaN and InAlN, ScAlN, because of its significant spontaneous polarization, promises to increase the operating frequency at high power. Impressive results on metal-polar ScAlN/GaN HEMTs were reported back in 2019 by a collaboration between researchers at the U.S. Air Force Research Laboratory and Qorvo.

The alternative to this, the N-polar GaN-based HEMT, has intrinsic advantages. It allows increases in operating frequency while maintaining high output power and addressing scaling challenges. We have pursued this particular design, and by controlling the lattice-polarity of the underlying GaN buffer, we have used MBE to demonstrate the first N-polar ScAlN HEMT structures on an on-axis sapphire substrate. We measured a Hall mobility of 564 $cm^2 V^{-1} s^{-1}$, a sheet electron concentration of 4.1×10^{13} cm^{-2}, and a sheet resistance as low as 271 Ω/sq.

Recently, we made further progress, demonstrating ferroelectricity in N-polar ScAlN/GaN heterostructures. These nearly lattice-matched heterostructures exhibit a highly uniform coercive field of around 4.6 MV/cm at 10 kHz, and a remnant polarization of around 90 $\mu C\ cm^{-2}$ across the whole wafer (see Figure 3).

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Our promising results could be surpassed with even more impressive ones by improving material quality and suppressing leakage. We are keen to explore electrical leakage paths in ferroelectric Sc-III-N films, as this will lay the foundation for establishing a robust growth strategy for addressing the leakage issue. Additionally, we will perform systematic microscopy studies to understand the polarization switching dynamics and the fatigue mechanism at scales from the micro to the atomic scale, enabling us to realise reliable ferroelectricity in fully epitaxial Sc-III-N heterostructures.

Another goal of ours is to develop nitride-ferroelectric-based electronic, optoelectronic and quantum devices and systems that are CMOS compatible and capable of combining high frequencies with high powers, a high efficiency and a low power consumption. Such devices could be deployed in automobile/aircraft/turbine engines, smart/electrical vehicles, 5G/6G communication technologies, big data analysis, the Internet of Things, and quantum sensing and communication. As an emerging member of third-generation semiconductors, as well as the ferroelectrics family, Sc-III-N exhibits great potential to be a unicorn in all these applications. In our recent works, we have also reported exciting results on photovoltaic detectors, memristors, transistors, and acoustic resonators.

Bright prospects for nitride ferroelectrics

From a fundamental material discovery perspective, the recent demonstration of nitride ferroelectric semiconductors has showcased the feasibility of developing a portfolio of new ferroelectrics by incorporating in III-nitride semiconductors a range of rare-earth elements, such as yttrium, lanthanum and lutetium; another potential addition is boron. This avenue offers unprecedentedly rich opportunities for strain, alloy, quantum and entropy engineering.

For device development, an intuitive approach is to combine nitride ferroelectrics with state-of-the-art III-nitride devices, such as HEMTs, LEDs, laser diodes, photodetectors, waveguides and resonators. This move could enhance device performance and tunability, and add programmability, data storage and computing capabilities.

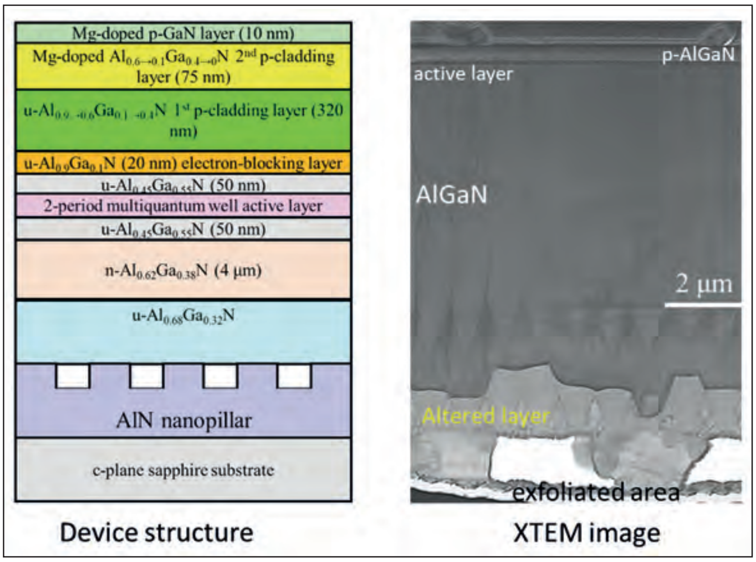
One recent experimental breakthrough has been the overcoming of Boltzmann's Tyranny by using the negative capacitance in ferroelectric materials. This advance highlights that nitride ferroelectrics will provide new opportunities for developing low-power-consumption transistors.

Ten years ago, the discovery of ferroelectricity in hafnium-based materials renewed interest in ferroelectrics. Now, this topic has been revitalised again, with the discovery of nitride ferroelectrics fuelling a new wave of research on ferroelectric semiconductor devices.

Exfoliating AlGaN films

When high pressure water is applied to an AlGaN heterostructure featuring AlN nanopillars, this can liberate the device layers from the substrate

THE LACK of a satisfactory method for exfoliating insulating substrates, which is key to the realisation of vertical devices, is holding back the performance of AlGaN-based devices. But this barrier can now be overcome, thanks to a technique developed by a team of engineers from Japan. They have devised a process for freeing AlGaN-based device structures from their substrate, via immersion of a sample in water heated to 115 °C and pressurised to 170 KPa.



➤ A cross-sectional transmission electron microscopy image of the AlGaN-based heterostructure indicates that exfoliation takes place at the AlN nanopillar area.

This approach, developed by a partnership between Meijo University, Mie University and Osaka University, allows AlGaN-based LEDs to replicate the architecture of their high-power GaN cousins produced by laser lift-off. Note that applying laser-lift off to AlGaN-based LEDs is not ideal, as aluminium droplets form, inhibiting exfoliation; while another candidate, electrochemical etching, requires application of an electric current, limiting the size of the exfoliation area.

The team hopes that its approach, involving the growth of AlGaN heterostructures on a triangular lattice of pillars that are 1.2 μm high, 400 nm wide, and have a period of 1 μm, will be employed for fabricating high-power UV LEDs and lasers. Such devices could serve in several applications, including sterilization, biotechnology, medicine and processing.

Spokesman for the Japanese collaboration, Motoaki Iwaya from Meijo University, told *Compound Semiconductor* that the idea for the team's approach originated from a student's heating and cleaning of a device wafer, prior to processing. At that point there were that signs that part of the wafer was peeling off; inspection under various microscopes revealed the formation of a reaction layer.

There are only a few reported cases of the reaction of water and single crystals of AlN and AlGaN. "But I knew that water reacts with powder and polycrystalline AlN, so I thought that perhaps the nitrogen surface of AlN and AlGaN were reacting to form products," remarked Iwaya. "I also wondered if this could be utilized for substrate exfoliation."

Building on this idea, Iwaya and co-workers considered how water could penetrate into voids just several hundred nanometres in size. Any attempt to do so is hampered by the surface tension of the water. To address this, the team used an approach inspired by a clip on a TV that Iwaya watched many years ago, on how to introduce a liquid into a sauce bottle – the variant of this employed by the researchers included immersing the sample in a beaker filled with water, before placing that entity in an airtight polycarbonate container that is evacuated, with a vacuum maintained for 5 hours.

Also critical to success is the use pressurised water. "We were not sure if this would work experimentally, so we used a household electric pressure cooker for this experiment," revealed Iwaya, who added that they are now considering apparatus that could increase pressure, as this might speed the process.

Iwaya believes that refinements to their approach – it has already liberated 1 cm^2 samples with few additional dislocations, according to transmission electron microscopy – would enable this technique to be used for volume production of AlGaN-based devices.

Currently the most time-consuming part of the process involves inserting water between the pillars. "If the viscosity of water can be reduced by increasing the void size, or by mixing it with a less viscous liquid such as alcohol, it should be possible to shorten the time required to introduce water," argued Iwaya.

Plans for the team include: clarifying the exfoliation mechanism; increasing the diameter of exfoliation, ideally to encompass 2-inch wafers; and developing vertical UV LEDs and UV laser diodes.

"We are also looking into the production of thinner-film LEDs that can achieve a high-light-extraction efficiency, which has been applied to blue LEDs," added Iwaya.

REFERENCE

➤ E. Matsubara *et al*. Appl. Phys. Express **15** 116502 (2022)

Accelerating HVPE of AlN

Quashing parasitic reactions enables HVPE to speed the growth of high-quality AlN

A COLLABORATION between researchers in Japan and Poland is claiming to have made a significant breakthrough in the development of high-structural-quality AlN substrates with excellent transparency in the UV.

The team's use of a new Taiyo Nippon Sanso HVPE reactor that supresses parasitic reactions has enabled the deposition of AlN at a growth rate of 150-170 μm/hr, The resulting AlN retains the structural quality of the seed grown by physical vapour transport (PVT), while reducing the density of impurities that inhibit transparency in the deep UV.

The team – a partnership between researchers at Tokyo University of Agriculture and Technology, Tokuyama Corporation, Fujitsu Limited, and the Institute for High Pressure Physics, Poland – hopes its advance will aid the productivity of freestanding AlN substrates. They are said to be an attractive foundation for the production of deep-UV LEDs and laser diodes that could be deployed for inactivation of viruses, sterilization, resin curing and processing.

Today, these deep-UV emitters are grown on either single-crystal bulk AlN substrates or engineered substrates, formed by growing a thin film of AlN on single-crystal sapphire. The latter ensures higher productivity, due to the availability of low-cost, large diameter sapphire, but dislocations are as high as mid-10^7 to 10^{10} cm^{-2}, impairing device performance and reliability. Bulk AlN grown by PVT has a far lower dislocation density, typically 10^3 cm^{-2}, but substrates are pricey, limited in availability, and have high concentrations of carbon, oxygen and silicon impurities that diminish transparency below 300 nm.

Some of the researchers involved in the latest work have previous experience of using HVPE to grow AlN. For a previous study that employed a PVT-grown seed and selective generation of $AlCl_3$, which does not react with quartz, the HVPE approach yielded crystalline AlN with a deep-UV transparency and a dislocation density of the order of 10^3 cm^{-2}. However, parasitic reactions limited the growth rate to several tens of microns – that's far slower than the growth rate for PVT, which can be 150-170 μm/hr at 2230 °C.

The team's Taiyo Nippon Sanso HVPE_A111 quartz-based horizontal reactor supresses these parasitic reactions. It features an up-stream source zone heated by an electric furnace and a downstream growth zone heated by RF induction.

Using $AlCl_3$ as the source of aluminium, supplied via a nozzle made of BN to prevent parasitic reactions, and NH_3 for the source of nitrogen, the team grew films of AlN on 6 mm by 7 mm by 0.52 mm pieces of AlN(0001), cut from a 35 mm-diameter HexaTech wafer made by PVT. Those pieces provided the foundation for the growth of AlN at a range of growth rates up to 156 μm/hour

Inspecting films around 50 μm-thick with an optical microscope revealed that the growth rate influences morphology. A rate of 7.6 μm/hour produced a very smooth surface, while around 50 μm/hour or more induced a shift to a three-dimensional growth mode, resulting in hexagonal pyramidal hillocks. However, even at the fastest growth rate of 156 μm/hour, which led to hillocks with a typical width and height of 250 μm and 2 μm, respectively, no AlN microcrystals were found to fall on the surface.

According to X-ray diffraction rocking curves along a symmetric and skew symmetric plane, it is possible to grow homoepitaxial layers with a structural quality comparable to that of PVT-grown AlN, even when the growth rate exceeds 150 μm/hr.

Investigating the samples with secondary-ion mass spectrometry revealed that with increasing growth rate concentrations of oxygen and chlorine fell, while that of silicon went up. The researchers suggest that higher concentrations of silicon impurities at faster growth rates could be due to the appearance of facets on the surface, or an increase in AlCl relative to $AlCl_3$. As quartz in the HVPE tool reacts with AlCl to generate the doping gas $SiCl_4$, the team recommends removing quartz glass from the growth chamber to minimise the addition of silicon impurities.

To assess the optical characteristics of the HVPE-grown AlN, the researchers produced a 40 μm-thick free-standing substrate by the removal of PVT-AlN, followed by chemical-mechanical polishing. This sample has a steep optical absorption edge at 207 nm, and a high transmittance at longer wavelengths. There is an absence of an absorption band around 450 nm – it is observed in free-standing AlN substrates produced at lower growth rates, due to a higher level of oxygen impurities.

The team are now investigating growth of thicker homoepitaxial layers at rates higher than 150 μm/hr.

REFERENCE

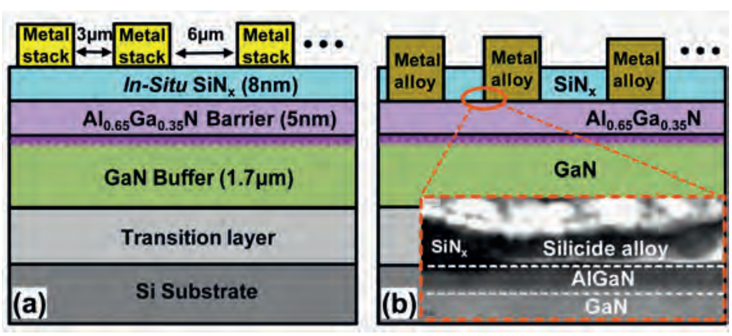
➤ Y. Kumagai *et al.* Appl. Phys. Express **15** 115501 (2022)

SiN trims the resistance of high-speed HEMTs

In-situ addition of SiN reduces the contact resistance of aluminium-rich HEMTs

ENGINEERS FROM Xidian University, China, have significantly cut the contact resistance of GaN-based HEMTs with an aluminium-rich AlGaN barrier layer by *in-situ* insertion of SiN.

Their triumph promises to aid the development of HEMTs operating above 40 GHz. In these devices, the aluminium-rich AlGaN barrier enhances the transistor's speed, but hampers the realisation of a low contact resistance.



➤ After adding the metal contact to the heterostructure with a SiN layer (a), the annealing step creates a metal alloy that's in contact with the $Al_{0.65}Ga_{0.3}5N$ barrier (b).

According to the team, their approach is simpler and cheaper than that of alternatives for realising high-frequency AlGaN/GaN HEMTs with a low contact resistance, such as silicon implantation and the re-growth of a heavily doped *n*-type GaN layer.

Spokesman for the researchers, Zhihong Liu, told *Compound Semiconductor* that the idea for inserting a SiN layer came from previous experimentals.

He remarked: "We knew that a thin layer of silicon, deposited in a certain way, could help the ohmic contact formation in GaN HEMTs; and at high temperatures the quality of SiN will degrade and become very leaky – so a thin layer of SiN may decompose and the remaining silicon help with the ohmic contact."

Liu and co-workers investigated this possibility with an $Al_{0.65}Ga_{0.35}N$/GaN HEMT featuring a thin layer of SiN, grown *in-situ* on the surface of the heterostructure.

This study began by taking a sapphire substrate and growing, by MOCVD, a 1.7 μm-thick unintentionally doped GaN buffer, followed by a 5 nm-thick $Al_{0.65}Ga_{0.35}N$ barrier and a 8 nm SiN layer. According to room-temperature Hall mobility measurements, this structure has a two-dimensional electron gas density of 2.2 x 10^{13} cm^{-2} and a mobility of 1190 cm^2 V^{-1} s^{-1}.

After planar isolation by argon-ion implantation, the team formed ohmic contacts through the addition of a Ti/Al/Ni/Au metal stack, annealed under nitrogen gas for 30 s at 850 °C. It is claimed that the composition of the stack and the annealing conditions is optimised. For comparison, the researchers fabricated a control, identical except for omission of the *in-situ* SiN layer.

Turning to the transfer length method, with electrode spacings from 3 μm to 18 μm, revealed that adding of SiN reduced the contact resistance from 0.320 Ω mm to 0.175 Ω mm and cut the specific contact resistivity from 2.84 x 10^{-6} Ω cm^2 to 8.45 x 10^{-7} Ω cm^2. A combination of resistance-related measurements between 300 K and 450 K and modelling of this data allowed the team to deduce the primary transport mechanism in ohmic contacts at metal-semiconductor interfaces for both types of device.

That approach revealed that thermionic field emission governs transport in the ohmic contact of the sample with the SiN layer. This behaviour is beneficial in GaN-based electronic devices, because they often operate at high junction temperatures. In the control, field emission is thought to dominate, due to the thinness of the $Al_{0.65}Ga_{0.35}N$ layer and its larger barrier height.

Inspecting the contacts with high-resolution transmission electron microscopy revealed that the 8 nm-thick SiN layer decomposed under annealing. It's suggested that the dark clumps observed at the interface are TiN. They are partially surrounded by gold – its presence is confirmed energy-dispersive X-ray spectroscopy.

Liu admitted that he is still to optimise the thickness of the SiN layer, which has a tremendous impact on the resistance.

The team also applied its technology to an AlN/GaN HEMT, grown on silicon, and recorded high values for both the cut-off frequency and the maximum oscillation frequency. "This work is submitted to another journal and is still under review," added Liu.

The next goals for the engineers are to try and improve the contacts by tuning the thickness of SiN, and using their recent breakthrough to develop millimetre-wave and terahertz HEMTs.

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➤ D. Hanghai *et al*. Appl. Phys. Lett. **121** 172102 (2022)

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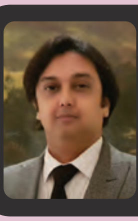

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