POWER ELECTRONICS WORLD
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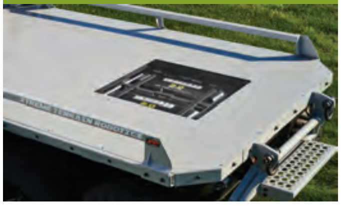
Electrifying industrial equipment choices



Adoptions by Automotive Market

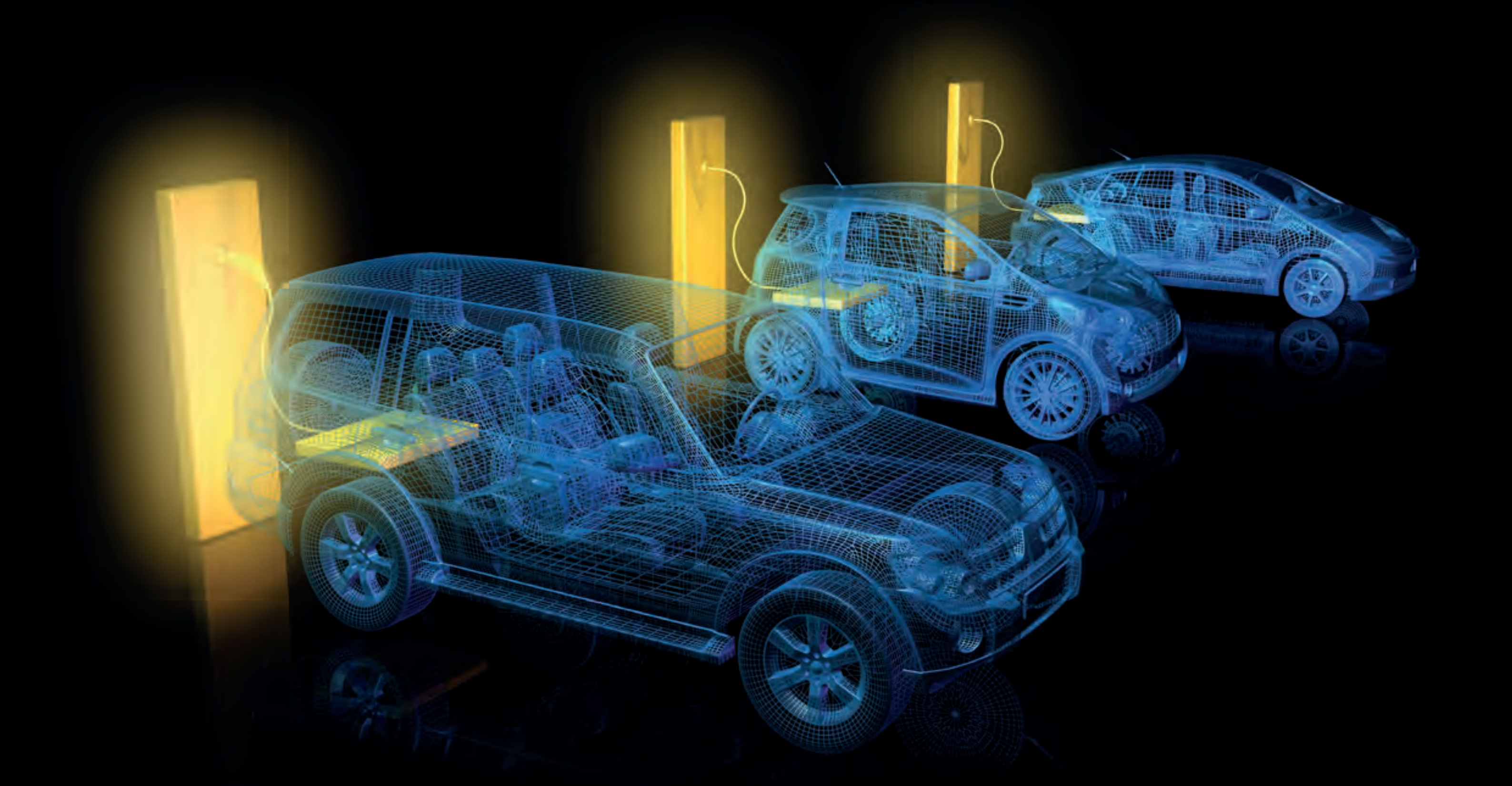
Shifting to 200 mm silicon carbide

Enkris: breaking the 300 mm barriers

Medium-voltage with vertical GaN devices

Electrifying heavy vehicle transport faces challenges

By Cressel




AIXTRON
AIXTRON

editor'sview

By Mark Andrews, Technical Editor

Power device sales soar as supply chain worries linger

AS THIS FOURTH 2021 edition of PEW Magazine finalizes, sales across broad electronics and power device segments have again set and broke multiple records. Demand remains especially strong for the devices our industry produces as well as the tools it takes to make ICs. 2022 (assuming a broadening pandemic recovery,) should be a great, great year—right? Well, there is still the ***little*** matter of supply chain gaffs affecting so many areas of our lives that getting from A to B continues to redefine normal.

While I won't attempt to turn this column into a 2021 review, it would be remiss to not highlight landmark trends as we consider where we may find ourselves in the New Year. Weathering the ups and downs of a post-pandemic world and the most semiconductor-centric industrial buildup in recent memory are noteworthy in and of themselves. A few additional highlights and New Year's bellwethers:

- While sales this year of everything silicon, silicon carbide, compound-semi or any HVM hybrid combination has demonstrated, 2021 was a roller coaster ride that will not abate anytime soon. According to all the manufacturers of a size worth noting, every bit of productivity is being wrenched out of the system even as delivery problems for electronics materials and end use products will continue into mid-2022 or longer.
- More and more major OEMs are making their own high-end microelectronics (Amazon, Apple, Google, etc.,) and other industries are 'cross-pollinating' to ensure future supplies as we see in Ford linking with Globalfoundries, GM with Wolfspeed and fab building partnerships further linking the US, Europe, Korea, Japan, China, Taiwan and other major Asia manufacturing centers.

In this edition of Power Electronics World we explore Yole Developpement's insights on the pandemic's long range effects on semiconductor and photonic/broadband markets. The continuing growth of EV sales, digitalization and changing work/home electronic equipment needs will continue to drive sales. We look at evolving power alternatives; the latest power device research; and instances demonstrating that Silicon Carbide (SiC) and Gallium Nitride (GaN) now dominate power electronics innovations for inverters, renewable energy and vehicle electrification.

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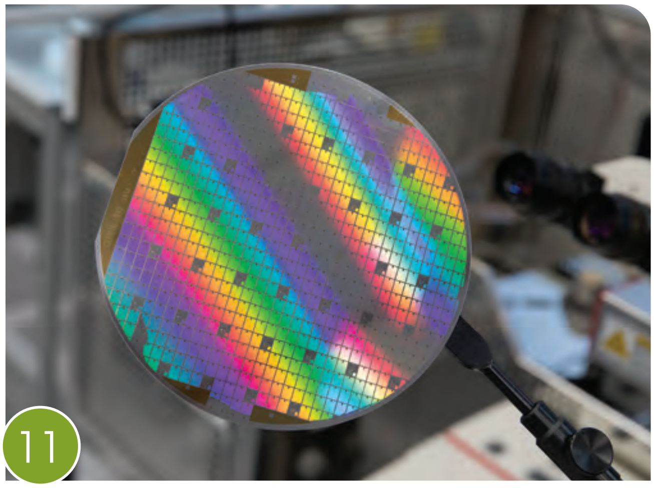
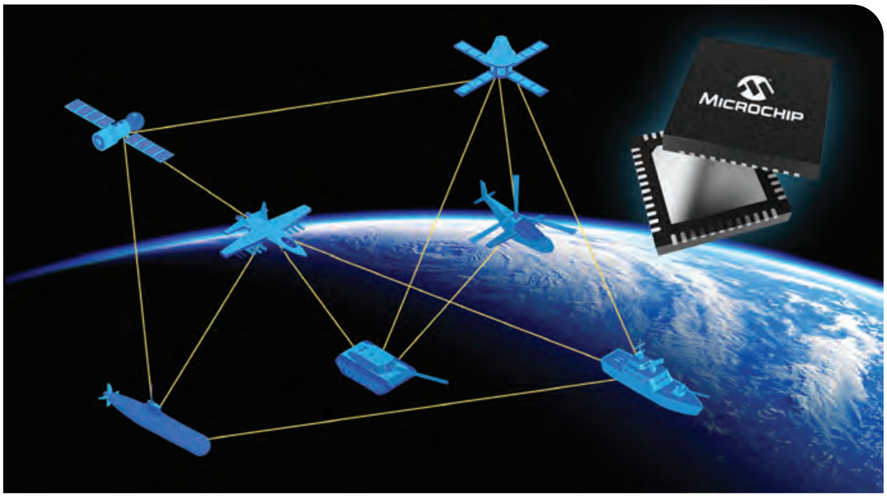


Microchip expands RF GaN range



Microchip Technology has announced a significant expansion of its GaN RF power device portfolio with new MMICs and discrete transistors that cover frequencies up to 20 GHz. The devices combine high power-added efficiency (PAE) and high linearity to deliver new levels of performance in applications ranging from 5G to electronic warfare, satellite communications, commercial and defense radar systems and test equipment.

Like all Microchip GaN RF power products, the devices are fabricated using GaN-on-SiC technology that provides the best combination of high-power density and yield, as well as high-voltage operation and longevity of more than 1 million hours at a 255degC junction temperature.

They include GaN MMICs covering 2 to 18 GHz, 12 to 20 GHz, and 12 to 20 GHz with 3 dB Compression Point (P3dB) RF output power up to 20 W and efficiency up to 25 percent, as well as bare die and packaged GaN MMIC amplifiers for S- and X-band with up to 60 percent PAE, and discrete high electron mobility transistor (HEMT) devices covering DC to 14 GHz with P3dB RF output power up to 100W and maximum efficiency of 70 percent.

“Microchip continues to invest in our family of GaN RF products to support every application at all frequencies from microwave through millimeter wavelengths, and our product portfolio includes more than 50 devices, from low-power levels to 2.2 kW,” said Leon Gross, vice president of Microchip’s discrete products business unit. “Together the products announced today span 2 to 20 GHz and are designed to meet the linearity and efficiency challenges posed by the higher-order modulation techniques employed in 5G and other wireless networks, as well as the unique needs of satellite communications and defense applications.”

Microchip’s portfolio of RF semiconductors in addition to GaN devices ranges from GaAs RF amplifiers and modules to low-noise amplifiers, front-end modules (RFFEs), varactor, Schottky, and PIN diodes, RF switches and voltage variable attenuators.

In addition, the company provides high-performance surface acoustic wave (SAW) sensors and microelectromechanical systems (MEMS) oscillators and highly integrated modules that combine microcontrollers (MCUs) with RF transceivers (Wi-Fi® MCUs) that support major short-range wireless communications protocols from Bluetooth® and Wi-Fi to LoRa®.

Microchip provides board design support to help with design-ins, as do the company’s distribution partners. The company also provides compact models for the new GaN products that let customers more easily model performance and expedite the design of the power amplifiers in their systems.

Power Integrations’ new InnoSwitch3-TN ICs Slash Energy Waste by 75%

POWER INTEGRATIONS has introduced the highly integrated InnoSwitch 3-TN off-line, CV/CC flyback switcher IC. Offered in a safety-qualified, compact MinSOP-16A package and incorporating a 725 V primary MOSFET, isolated feedback, synchronous rectification and secondary-side control, InnoSwitch3-TN ICs enable power supplies that are simple to design and ideal for appliance and industrial auxiliary applications up to 21 W.

Silvestro Fimiani, senior product marketing manager at Power Integrations said: “Our new InnoSwitch3-TN devices support the high output current needed in smart-connected appliances at efficiencies of up to 90%, compared to traditional approaches such as buck regulators that are often less than 60% efficient. InnoSwitch3-TN ICs incorporate all feedback components while supporting isolated, non-isolated, single and multi-output designs for the most compact, flexible auxiliary power supply solution.”

The advanced InnoSwitch3-TN flyback controller delivers constant efficiency across the load range and less than 5 mW no-load consumption. The flexibility afforded by FluxLink communication technology means that positive and negative outputs are easily achieved. InnoSwitch3-TN ICs can be used in a 5 V single-output power supply, with two positive output rails, or with both positive and negative rails, without any external feedback components. Safety-rated FluxLink technology also ensures reliable synchronous rectification and accurate constant voltage and constant current on the output. The low forward drop of the SR MOSFET also ensures excellent cross-regulation performance. Comprehensive safety features include output over-current and over-temperature protection. The small MinSOP package and low number of external components required for a full PSU design make the InnoSwitch3-TN ideal for compact implementations.

EVs are driving 6-inch SiC wafer demand

THE EV MARKET'S demand for longer driving ranges and shorter charging times, is in turn pushing car makers to produce models with high-voltage 800V charging architectures. These include the Porsche Taycan, Audi Q6 e-tron, and Hyundai Ioniq 5.

According to TrendForce's latest investigations, demand from the global automotive market for 6-inch SiC wafers is expected to reach 1.69 million units in 2025 thanks to the rising penetration rate of EVs and the trend towards high-voltage 800V EV architecture.

The arrival of the 800V EV charging architecture will bring about a total replacement of silicon IGBT modules with SiC power devices, which will become a standard component in mainstream EV VFDs (variable frequency drives). As such, major automotive component suppliers generally favor SiC components. In particular, Tier 1 supplier Delphi has already begun mass producing 800V SiC inverters, while others such as BorgWarner, ZF, and Vitesco are also making rapid progress with their respective solutions.

EVs have become a core application of SiC power devices. For instance, SiC usage in OBC (on board chargers) and DC-to-DC converters has been relatively mature, whereas the mass production of SiC-based VFDs has yet to reach a large scale. Power semiconductor suppliers including STM, Infineon, Wolfspeed, and Rohm have started collaborating with Tier 1 suppliers and automakers in order to accelerate SiC deployment in cars.

Upstream supply of SiC substrate materials will become the primary bottleneck of SiC power device production, since SiC substrates involve complex manufacturing processes, high technical barriers to entry, and slow epitaxial growth.

The vast majority of n-Type SiC substrates used for power semiconductor devices are 6 inches in diameter. Although major IDMs such as Wolfspeed have been making good progress in 8-inch SiC wafer development, more time is required for not only raising yield rate, but also transitioning power semiconductor fabs from 6-inch production lines to 8-inch production lines.

6-inch SiC substrates will likely remain the mainstream for at least five more years. On the other hand, with the EV market undergoing an explosive growth and SiC power devices seeing increased adoption in automotive applications, SiC costs will in turn directly determine the pace of 800V charging architecture deployment in EVs.

Boston Semi receives orders for high power IC handling solutions

BOSTON SEMI EQUIPMENT (BSE), has announced that it received multiple orders from a major automotive IC supplier. The orders are for BSE's Zeus gravity test handler configured for high power IC testing applications, along with enhanced high voltage upgrades to increase the peak voltage level of Zeus handlers already in production.

The Zeus handler is designed to enable the highest voltage levels available in a production handler for testing MOSFET, IGBT, GaN and SiC power semiconductors. The BSE high voltage solution provides superior voltage isolation with a voltage range up to 8.4kV RMS (11.8kV peak). Handling solutions for voltages up to 14kV peak are in development.

"Boston Semi Equipment's high voltage handling capability within the Zeus handler delivers industry-leading performance backed by 25 years of experience," stated Kevin Brennan, vice president of marketing at BSE. "The Zeus high voltage solution provides high-isolation, ideal contacting conditions for accurate partial discharge testing, and safety features our customers require when validating the performance of packages that handle thousands of volts. BSE handlers are interfaced with high voltage testers at production sites worldwide, ensuring the quality of our customers' devices."

The Zeus High Voltage handler is available in configurations from one to four sites with octal configurations possible. Safety features throughout the handler ensure safe operation. Zeus offers the features and performance needed by today's power IC test cells at a more affordable price than the competition and is backed by Boston Semi Equipment's worldwide service team.

Imec takes power GaN integration one step further

At the 2021 International Electron Devices Meeting (IEEE IEDM 2021), Imec will presents the successful co-integration of high-performance Schottky barrier diodes and depletion-mode HEMTs on a p-GaN HEMT-based 200V GaN-on-SOI smart power IC platform developed on 200 mm substrates.

The addition of these components enables the design of chips with extended functionality and increased performance that takes monolithically-integrated GaN power ICs one step further. The achievement paves the way towards smaller and more efficient DC/DC convertors and Point-of-Load convertors.

GaN power electronics are today still dominated by discrete components driven by an external driver IC that generates the switching signals. However, to take full advantage of the fast-switching speed GaN offers, monolithic integration of power devices and driver functions is recommended. Imec has already successfully demonstrated the monolithic co-integration of a half-bridge and drivers together with control and protection circuits that are key to an integrated all-GaN power IC in one chip.

One of the main hurdles to boost the full performance of GaN power ICs remains finding a suitable solution for the lack of p-channel devices in GaN with acceptable performance. CMOS technology uses complementary and more symmetrical pairs of p- and n-type field effect transistors (FETs), based on the mobilities of holes and electrons for both types of FETs. However, in GaN, the mobility of holes is about 60 times worse than that of electrons. That means that a p-channel device, where holes are the principal carriers, would be 60 times larger than the n-channel counterpart and highly inefficient. A widespread alternative is replacing the P-MOS by a resistor. Resistor-Transistor Logic (RTL) has been employed for GaN ICs but shows trade-offs between switching time and power consumption.

“We have improved the performance of GaN ICs by using a combination of enhancement-mode and depletion-mode switches, called e-mode and d-mode HEMTS. By extending our functional e-mode HEMT platform on SOI with co-integrated d-mode HEMTS, we can now take the step from RTL to direct-coupled FET logic which is expected to improve the speed and reduce the power dissipation of the circuits,” said Stefaan Decoutere, program director GaN power systems at Imec.

Another important component for co-integration on GaN power ICs is a Schottky barrier diode. Compared to their silicon counterparts, GaN Schottky diodes combine higher blocking voltages with reduced switching losses.

“We have successfully extended our 200 V GaN-on-SOI e-mode HEMT GaN ICs platform with monolithically-integrated high-performance Schottky barrier diodes and d-mode HEMTs which brings us a step closer to smart power ICs based on GaN. This GaN-IC platform is available for prototyping through our multi-project-wafer (MPW) service,” adds Stefaan Decoutere.

“Our platform is ready for transfer to partners. We’re looking for foundries, but also design houses and end-users. The next step will be to develop and release a 650 Volt version of the platform. Target

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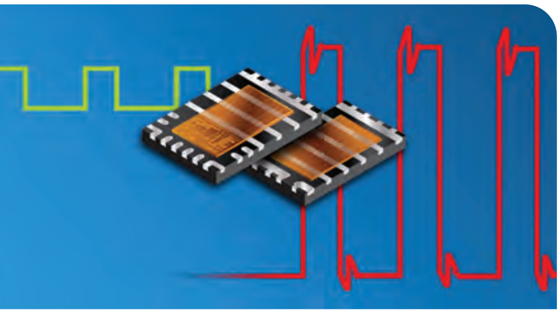
EPC announces GaN Chipset for 48V DC-DCs

EPC has announced a 100V, 65A integrated circuit chipset designed for 48V DC-DC conversion used in high-density computing applications and in 48 V BLDC motor drives for e-mobility, robotics, and drones.

The EPC23101 eGaN IC plus EPC2302 eGaN FET offers a new ePower Chipset capable of a maximum withstand voltage of 100 V, delivering up to 65 A load current, while capable of switching speeds greater than 1 MHz.



Key features of the EPC23101 integrated circuit using EPC’s proprietary GaN IC technology include integrated 3.3 mOhm RDS(on) high side FET with gate driver, input logic interface, level shifting, bootstrap charging, gate drive buffer circuits and gate driver output to drive external low side eGaN FET

The EPC2302 eGaN FET offers a super small RDS(on), of just 1.8 mOhm, together with very small QG, QGD, and QOSS parameters for low conduction and switching losses. Both devices feature a thermally enhanced QFN package with exposed top with optimized pinout between the two devices. The combined chipset footprint, is 7 mm x 5 mm, offering an extremely small solution size for the highest power density applications. When operated in a 48 V to 12 V buck converter, the EPC23101 + EPC2302 chipset delivers 96 percent efficiency at 1 MHz switching frequency and 97 percent efficiency at 500 kHz switching frequency and can deliver 65 A with less than 50 °C temperature rise.

EPC says that the ePower family of products is designed to make it easy for designers to take advantage of the significant performance improvements made possible with GaN technology.

Integrated devices are easier to design, easier to layout, easier to assemble, save space on the PCB, and increase efficiency.

Navitas sets its sights on data centers

GaN COMPANY Navitas Semiconductor has announced its expansion into higher-power markets with the opening of a new design centre dedicated to bringing next-generation GaN power ICs and associated high-efficiency, high-power-density systems to data centres.

The new design centre, based in Hangzhou, China, hosts a team of power system designers with capabilities across electrical, thermal and mechanical design, software development, and complete simulation and prototyping capabilities. Navitas says that data centre power customers will be supported worldwide by the new team, from concept to prototype, through to full qualification and mass production.

The design centre will develop schematics, layouts, and firmware for data centre power supplies.

Additionally, there will be multiple partnerships created for magnetics, thermal substrates, and other materials to assist customers to optimise their power supply designs.

Navitas estimates that an upgrade from legacy silicon to new GaN could deliver energy savings up to 40 percent, and save $1.9B/year in data centre electricity costs worldwide. Data centre supplies are rated to meet tough efficiency criteria, with the extreme 'Titanium' grade demanding 96 percent efficiency at 50 percent load. These new benchmarks are not only enabled by GaN technology but also demanded by legislation such as the European Union's 'Directive 2009/125/EC, 2019 Annex' which states that data new centre power supplies must meet 'Titanium' level of efficiency from January 1st, 2023.

"The Navitas Data centre team has the new technical skills of GaN power ICs plus the experience of real power supply design and qualification," said Charles Zha, VP and GM of Navitas China. "The first proof point is a 1.2kW 'Titanium plus' design that not only exceeds the highest efficiency standards for data centre power supplies, but is also value-engineered to be lower cost than legacy silicon designs. After this, it's on to 2.2kW and 3kW platforms."

The 1.2kW design was developed in collaboration with Boco and FRD of Hangzhou, and the power supply is now under evaluation for mass production in 2022. Golden Yin, Boco's CEO said "GaNFast power ICs are easy-to-use, digital-in, power-out building blocks that have accelerated time-to-prototype and first-time-right designs." Ray Gu, GM of Power Supply BU at FRD stated "GaNFast power ICs are essential to achieving Titanium Plus efficiency, a critical milestone for next-generation datacentre power supplies. This will help FRD strengthen its product portfolio and provide comprehensive solutions to enterprise customers".

"As data and communications continue their exponential growth, it is critical for data centres to upgrade to GaNFast power ICs to reduce costs, maximize energy savings and reduce CO_2 emissions," said Gene Sheridan, co-founder and CEO. "As a critical expansion market, we recruited ahead of our recent IPO funding, and that faith in our data centre design team is already paying dividends. By working in collaboration with data centre engineers around the world, we can accelerate adoption of GaN-based data centres and make a significant impact on energy savings, electricity costs and CO_2 emissions."

Manufacturing a GaN power IC has up to a ten times lower CO2 footprint than for a silicon chip, and considering use-case efficiency, material size and weight benefits, then each GaN power IC shipped can save 4 kg of CO_2.

Overall, GaN is expected to address a 2.6 Gton/yr reduction in CO_2 emissions by 2050.

Onsemi completes acquisition of GT Advanced Technologies

ONSEMI has announced that it has completed its acquisition of GT Advanced Technologies, a producer of SiC. The acquisition enhances Onsemi's ability to secure and grow supply of SiC.

Onsemi's customers will benefit from GTAT's extensive experience in crystalline growth as well as its impressive technical capabilities and expertise in the development of wafering-ready SiC. SiC is a key component of next-generation semiconductors that provide technical benefits and improve system efficiency in many applications, including electric vehicles (EVs), EV charging and energy infrastructure. Onsemi intends to scale and accelerate GTAT's development of SiC to assure customers supply of critical components and further commercialize intelligent power technologies.

"We are thrilled to have completed this acquisition, which enables us to boost SiC supply as we carry out our mission of building a sustainable future," said Hassane El-Khoury, president and chief executive officer of Onsemi. "As we move to a carbon free economy, SiC technology is a key driver to enable zero emissions in high efficiency electric vehicles, renewable energy and charging infrastructure. By integrating GTAT, Onsemi can now provide end-to-end power solutions from SiC crystal growth to fully integrated intelligent power modules."

El-Khoury continued, "We are proud to welcome GTAT's incredibly talented employees to the Onsemi family. Their experience and insights in the SiC space are second to none, and we look forward to working together to drive important new innovations that are critical to the growth of the sustainable ecosystem."

The acquisition reinforces Onsemi's commitment to make substantial investments in disruptive, high-growth technologies to drive differentiation and leadership, including in the SiC ecosystem.

Onsemi plans to invest in expanding GTAT's manufacturing facilities, supporting research and development efforts to advance 150mm and 200mm SiC crystal growth technology, while also investing in the broader SiC supply chain, including Fab capacity and packaging.

Bosch gives go-ahead for volume production of SiC chips

AFTER SEVERAL YEARS of development, Bosch is now starting volume production of SiC power semiconductors. “The future for SiC semiconductors is bright. We want to become a global leader in the production of SiC chips for electromobility,” says Harald Kroeger, member of the board of management of Robert Bosch GmbH.

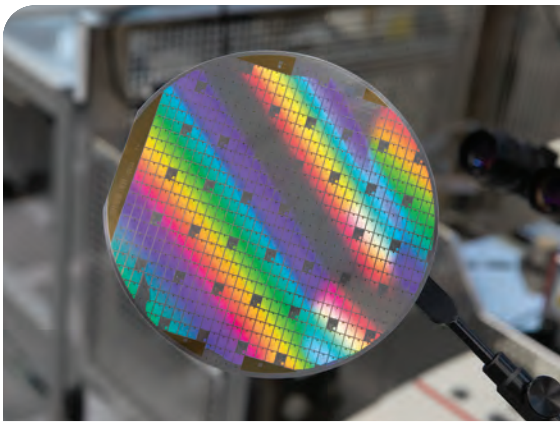
Two years ago, the supplier of technology and services had announced that it would push ahead with the development of SiC chips and enter production. For this, Bosch has developed its own manufacturing processes, which it has been using since the beginning of 2021 – initially as samples for customer validation. “Our order books are full, thanks to the boom in electromobility,” Kroeger says.

In the future, Bosch intends to expand its production capacity for SiC power semiconductors to a unit volume running into the hundreds of millions. With this in mind, the company has already started expanding the clean-room space at its Reutlingen plant. In parallel, work is also being done on the second generation of SiC chips, which will be even more efficient and should be ready for volume production as of 2022.

Bosch is receiving support for the development of these innovative manufacturing processes for SiC semiconductors from the German Federal Ministry for Economic Affairs and Energy (BMWi) as part of the “Important Project of Common European Interest (IPCEI) Microelectronics” program.

“For several years now, we have been providing support to help establish semiconductor production in Germany. Bosch’s highly innovative semiconductor production strengthens the microelectronics ecosystem in Europe and is a further step toward greater independence in this key field of digitalisation,” says Peter Altmaier, Germany’s Federal Minister for Economic Affairs.

Around the world, demand for SiC power semiconductors is rising. A forecast by the market research and consulting company Yole indicates that, between now and 2025, the SiC market as a whole will grow on average by 30 percent a year to over 2.5 billion dollars. At around 1.5 billion dollars, the SiC car market is expected to account for the lion’s share. In order to meet steadily increasing demand for these semiconductors, an extra 1,000 square meters were already added to the clean-room space at the Bosch wafer fab in Reutlingen in 2021. Another 3,000 square meters will be added by the end of 2023. The new space will house state-of-the-art production facilities for manufacturing SiC semiconductors using processes developed in-house. To achieve this, Bosch’s semiconductor experts are building on their decades of expertise in chip manufacturing. In the future, the company plans to manufacture the semiconductors on 200-millimeter wafers. Compared with today’s 150-millimeter wafers, this will deliver sizeable economies of scale. After all, it takes several months for a single wafer to pass through several hundred process steps in countless machines. “By producing on larger wafers, we can manufacture significantly more chips in one production run and thus supply more customers,” Kroeger says.



Soitec and Mersen announce strategic partnership

SEMCONDUCTOR MATERIALS company Soitec and Mersen, an expert in electrical specialties and advanced materials, have entered into a strategic technical partnership to develop a new family of polycrystalline silicon carbide (poly-SiC) substrates for the electric vehicle market.

Thanks to their respective experience in substrates and materials, the joint development by Soitec and Mersen of very low electrical resistivity poly-SiC substrates will optimize SiC power electronics components devised based on Soitec’s SmartSiC technology. The collaboration between the Mersen teams in Gennevilliers and the Soitec teams in Bernin and Grenoble will strengthen this development project. The teams will also be able to benefit from the expertise of the Soitec Substrate Innovation Center within CEA-Leti to validate the progress made in the industrialisation process.

Christophe Maleville, Soitec’s CTO, said: “By further pooling our materials and semiconductor expertise, we are able to produce substrates with very advanced performance. The results are compatible with our SmartSiC™ technology, and also exceed the specifications of our customers, which are the SiC power electronic circuit foundries. With its very low electrical resistivity, the poly-SiC substrate becomes a key element of our technology, and can vastly improve energy efficiency, thus making electric vehicles more efficient.”

Luc Themelin, CEO of Mersen, said: “This partnership demonstrates Mersen’s polycrystalline SiC expertise and our ability to develop a custom-design product compatible with Soitec’s technology. Thanks to this strengthened partnership, we will be able to offer the electronics industry a high-performance, cost-effective substrate for the production of power semiconductors, especially for the electric vehicle market.”

Electrifying heavy vehicle transport faces challenges

Reducing carbon emissions by converting passenger vehicles to electric powertrains is moving forward at an accelerated pace despite temporary setbacks seen through the pandemic and its resultant supply chain disruptions. Electrifying heavy-duty vehicles presents its own challenges that are being addressed across the UK and in global markets. **BY CRESSEL.**

THE UK's Department for Transport Statistics reports that there were 485,900 heavy goods vehicles (HGVs) licenced in the UK in 2020, but only 400 of these were battery electric powered. With HGVs being a significant contributor of carbon emissions, will we see an increase in electric power? Simone Bruckner, managing director of power resistor manufacturer Cressall, explores the potential of electrifying the UK heavy vehicle market and wider-ranging considerations outside the UK and Europe.

HGVs account for around 17 percent of greenhouse gas emissions while contributing to just five percent of vehicle miles. Switching from diesel or petrol to electric power reduces the tailpipe emissions of vehicles, while also providing performance benefits. However, electric HGVs remain in the early stages. For electric heavy vehicles to become commonplace, there is a need for further development of the technology.

Battery electric versus hydrogen fuel cell

A challenge of electrifying heavy vehicles is finding an energy storage solution that doesn't add too much weight, which would increase energy consumption. Batteries must also possess a long range, allowing long distance freight. The main contenders for reducing vehicle emissions are battery electric and hydrogen fuel cell electric. Battery Electric Vehicles (BEVs) use chemical energy that is stored in rechargeable battery packs and use electric motors for propulsion.

However, the range between charges is limited, making it not so suitable for HGVs travelling a few hundred miles a day. This is exacerbated by the lengthy charge time of BEVs, extending to many hours for heavy vehicles depending on the charger.

Fuel Cell Electric Vehicles (FCEVs) also use an electric motor for propulsion but with a much smaller battery pack, with the fuel cell constantly converting the hydrogen to electricity, which only emits water from the tailpipe. FCEVs typically have a longer range and shorter fill time than BEVs, making them a stronger candidate for long-distance vehicles. Furthermore, the fuel cells can be stacked together to scale up power for a heavy vehicle. Fuel cells are more compact and lightweight than electric batteries, and most of the fuel cell can be recycled at end of life.

However, the majority of hydrogen currently being produced is made using fossil fuels through steam reforming, meaning hydrogen power is not emission free when its whole lifecycle is considered. If developments are made that allow more hydrogen to be produced from renewable resources, then FCEVs can become a more environmentally friendly option.

Performance, reliability and safety

Electric vehicles (EVs) are generally more reliable than Internal Combustion Engine (ICE) vehicles as they consist of fewer moving parts, reducing the risk of breakdowns and the need for frequent servicing. Electric motors can deliver torque quickly with almost instant acceleration, making vehicles quicker to start. This is particularly beneficial for heavy vehicles that are carrying large loads on fast motorways or on an inclined gradient.

Heavy vehicles brake differently to cars, as they do not purely rely on their service brakes to slow down. Instead, they also use auxiliary and endurance braking systems, which don't overheat as quickly on long declines and reduce the risk of brake fade or failure of the service brakes. In electric heavy vehicles, this braking is regenerative, which minimises wear on the service brakes and adds charge and range to the battery packs.

However, if there is a failure in the system, or the battery pack's state of charge is unable to accept the charge, this could become dangerous. Using a dynamic braking resistor will dissipate the excess energy as heat to improve the safety of the braking system. Regenerative braking aided by braking resistors can also boost heating efficiency by feeding the dissipated energy back into the vehicle to heat the internal cabin. The resistor needs to be compact and meet the current ECE R13 Type –IIA endurance braking performance test. To pass this test, the resistor must allow the heavy vehicle to travel 6km at 30kph on a seven per cent decline with the endurance braking system active and without the service brakes overheating and failing.

Future uptake

Currently, the UK has banned the sale of petrol, diesel and hybrid cars from 2035 onwards. However, there have been talks on proposing a ban on diesel heavy goods vehicles by 2040 in order to remove all carbon emissions from freight transportation by 2050. The race for electrifying heavy vehicles is on, and there could be penalties in the future for those who do not use electric. With only 400 battery electric heavy vehicles in the UK in 2020, electrifying the heavy vehicle market is in its early stages. However, with potential diesel bans looming, we must power ahead into an electric HGV future.

Heavy vehicle electrification in North America

Medium- and heavy-duty vehicles make up more than 23 percent of carbon emissions on American motorways according to the United States Department of Transportation. While the US has not formally mandated deadlines for eliminating diesel-fuelled heavy vehicles from its roads as have the UK and the EU, public and private institutions are studying the prospect with keen interest since the operational costs of vehicles that are driven much more heavily than passenger automobiles represents 'low hanging fruit' in the quest to reduce carbon emissions, slow global warming, and address increasingly high fossil-fuelled vehicle operational costs. The United States Postal Service and large, privately held delivery companies including FedEx and UPS have already added medium-duty EVs to their fleets. Their high torque and relatively fast recharge times make medium-duty light trucks attractive alternatives to fossil-fuelled vehicles and are already increasing the number of deliveries a vehicle can make in a given period compared to legacy fleets.

Whilst the quest to reduce emissions is widely accepted for passenger cars as well as light trucks and medium-duty vehicles, the math essentially changes for heavy-duty long-haul vehicles that average 125 miles driven per day. With a carrying capacity of more than 26,000 pounds (18,800 kilos,) battery weight paired with recharge time make the proposition of electrifying heavy duty transport a problem still searching for ideal solutions.

One approach being studied involves battery swap stations that could reduce 'recharge' time to minutes, putting heavy duty vehicles back on motorways in about the same time it takes to refuel a conventionally powered vehicle. But this convenience comes at significant cost: double or even triple the expense for batteries that are swapped at stations along vehicle routes, not to mention a highly specialized infrastructure beyond multi-kilowatt hour fast charging terminals.

Not wanting to put all its eggs in one proverbial basket, the US heavy duty transport sector has been exploring alternatives beyond batteries including start-up companies like Nikola that are working on a hydrogen-powered fuel cell truck. These vehicles have the distinct advantage of being able to refuel within minutes, mirroring the refuelling experience of a conventional diesel lorry. However, scarce hydrogen infrastructure, especially outside of California and other test sites across the globe, has limited the growth of fuel cell trucks so far.

Most US transportation analysts as well as global experts expect electrification in one form or another will come to medium- and heavy-duty transport; however, the challenges of building vehicle recharging infrastructure and/or fuel cell centres is still being studied. That being said, the benefits of reducing carbon emissions, increasing the number of deliveries a vehicle can accomplish in a day and simplified maintenance are making the question more a matter of when it will occur, not if.

Make the right choice for electrifying industrial equipment

As battery technology continues to evolve, greater power density, extended lifetimes and higher efficiency are prompting more companies to consider rechargeable energy sources. The power experts at **BRIGGS & STRATTON EMEA** offer their insights to avoid mistakes and help ensure operational safety.

WHICH BATTERY power source is right for your equipment? The world is changing, and batteries are changing the way we use power as it grows into an increasingly in-demand power source.

However, choosing the right battery pack solution for your application may feel like unfamiliar territory. There are multiple parameters to consider (including voltage, safety, life cycle, and capacity) that make the process of selecting the best battery for your equipment a complex task. In this article battery manufacturers Briggs & Stratton break down the main differences between a lead acid battery and a lithium-ion battery.

The basics

Batteries have been powering our lives longer than you may think. The first commercial battery hit the market in 1898. Since then, batteries have evolved to power everything from our phones and TV remotes to our vehicles. With so many options on the market, it can be hard to know where to begin. Lead acid batteries are perhaps the most well-known as the earliest type of rechargeable battery; lead acid chemistries are popular for low cost and high surge currents, allowing lead acid cells to handle simple charging devices and mechanisms.

For that reason, many automobiles rely on lead acid batteries to power engine starters. Therefore, purely from an upfront cost perspective, lead-acid has an advantage as such batteries do not require sophisticated electronics to function.

On the other hand, lead acid batteries are notoriously heavy. And while weight is often thought of as a disadvantage, in some unique applications the heavier lead acid battery can be an advantage. For example, when using a forklift, the lead acid battery acts as a counterweight at the back to offset weight being carried in the front.

Overall, a lead acid battery gets the job done, but can be a cumbersome power source due to its weight and high internal resistance. Lead acid batteries also heat up when charged and heat is a wasted energy; in some cases lead-acid battery efficiency can drop to as low as 50 percent.

Lithium-ion

Making its debut more than a century after the lead acid battery, commercial lithium-ion batteries hit the market in 1991. Just like lead acid, a lithium-ion battery is rechargeable; however, many of the similarities end there as lithium-ion batteries require some sort of intelligence to function.

Lithium-ion batteries feature a high energy density and low self-discharge. They are monitored by a battery management system (BMS) — the intelligence component which monitors temperature, data on power utilisation and voltage; the BMS allows the ability to integrate with Internet of Things devices. Not only is lithium-ion more capable, the technology is also more efficient.

You can use about half of the capacity in a lead acid battery, whereas with lithium-ion we're able to get upwards of 93 percent efficiency. The self-discharge rate (discharge that occurs while the battery is in an open-circuit condition) also outpaces lead acid. You can set a lithium-ion battery on a shelf, and it will hold its charge for an extremely long period of time. Whereas if you set a lead acid battery on that same shelf, you could come back to a dead battery surprisingly quickly.

Life expectancy

Batteries used repeatedly lose a little capacity with every cycle; a battery's lifespan is heavily dependent on the quality of cell, type of cell and how hard the battery is used. In general, lithium-ion batteries tend to lose capacity at a slower rate; a good example is in the case of a golf cart. In this application we would expect the lithium-ion battery to last 4-10 times longer than the lead acid counterpart depending on how well each battery is taken care of. Therefore, in most circumstances a lead acid battery needs to be replaced more frequently.

Minimal replacement contributes to a battery's environmental impact as the production process involves the mining of metals and there are the pollutants involved with shipping and finally the safe disposal of the battery being replaced. Additionally, Lithium-ion batteries are five times lighter than a lead acid battery while providing the same amount of energy.

Safety first – watering

Lead acid batteries get thirsty. The plates in a lead acid battery need to be continuously soaked in a liquid mixture of sulfuric acid and water to operate correctly. Over time, the water portion of that mixture in flooded lead acid batteries, such as those used in golf carts or some forklifts, will need to be replenished. Over-watering can significantly damage the battery by diluting the electrolyte solution or causing the battery to overflow, while not watering at all can lead to performance issues.

With lithium-ion batteries this type of maintenance is not required, which increases the safety of operation. Performing maintenance, such as watering, on the modular components of a lead acid battery will put people in potential contact with dangerous materials.

Just as the name implies, lead acid batteries depend on the acid component to function, creating the risk of being exposed to caustic, dangerous chemistries when watering. As such, service technicians must wear acid-resistant goggles, a face shield, and gloves. This risk does not exist with lithium-ion.

Stay cool

The BMS is the brains of the battery. Whilst keeping tabs on the temperature of the battery may sound simple, the BMS is more than just a thermometer. To ensure the battery stays within its operating range, the BMS is constantly monitoring and measuring not only the temperature but also the charge and discharge currents, as well as the voltages of each individual cell bank.

The BMS also adds safety and durability features to the lithium-ion battery by protecting against over voltage and low voltage; it also provides short circuit protection while helping maintain temperatures to ensure battery life isn't lost due to hard conditions. Since the primary safety concern with improperly managed lithium-ion batteries is a thermal runaway event, the BMS is a critical component. When a lithium-ion battery exceeds its maximum allowable temperature range, it can go into a thermal runaway event – the temperature rises rapidly, releasing the battery's energy.

However, this won't occur when the battery is properly managed and protected with a BMS. On the other hand, lead acid batteries have no safety backups. If you short-circuit a lead acid battery, there's nothing the battery can do to protect itself or the user.

Sustainability

While all batteries contain materials that could be harmful to the environment if improperly disposed, lead acid batteries present the added risk of possible sulfuric acid and/or lead leakage if damaged or improperly stored. Both materials can contaminate soil and water and are linked to negative health effects in humans. Lithium-ion batteries are sealed, and not subject to the same ''leakage'' concerns as lead acid if properly handled and disposed.

In conclusion, making the correct battery choice depends on its application. A lead acid battery may fit the bill for some short-term applications where high surge currents are all that is needed and in situations where weight isn't a deciding factor.

For everything else, look to lithium-ion solutions for an intelligent battery that can provide superior performance over the lifetime of your equipment.

Compound semiconductor adoption by automotive market

The EV/HEV race has begun. More than $300B of EV/HEV investments have been announced by different OEMs, clearly confirming the automotive industry's commitment to governmental CO2 reduction targets.

BY AHMED BEN SLIMANE, TECHNOLOGY & MARKET ANALYST AT YOLE DÉVELOPPEMENT

INDEED, the market figures are promising. The electrification strategy differs for each OEM, particularly within different regions, but there is a common goal to increase the share of battery electric vehicles (BEV) in their fleet. Hybrid electrification remains an option for the coming 10-15 years, although it does not meet the long term carbon neutrality.

New players from different technology areas (material and equipment suppliers, power electronic device manufacturer, system integrators, car makers…) are entering EV/HEV business. New divisions or joint ventures, fully dedicated to EV/HEVs are being established by many companies. The strong technology requirements and at the same time tough product qualification challenges call for development of new power electronic technologies. The high volume demand for EV/HEV attracts many players to be first to develop and implement such new solutions. In addition to already big EV/HEV market, the newly developed solutions can be also implemented in other applications areas, so further increasing business opportunities. But on the other side, there are some technology requirements specific for non-EV/HEV applications (higher device voltage, long lifetime, etc.). Some players might still find nice business opportunities in such application, instead of competing with growing number of players involved in EV/HEV business. In any case, for both EV/HEV

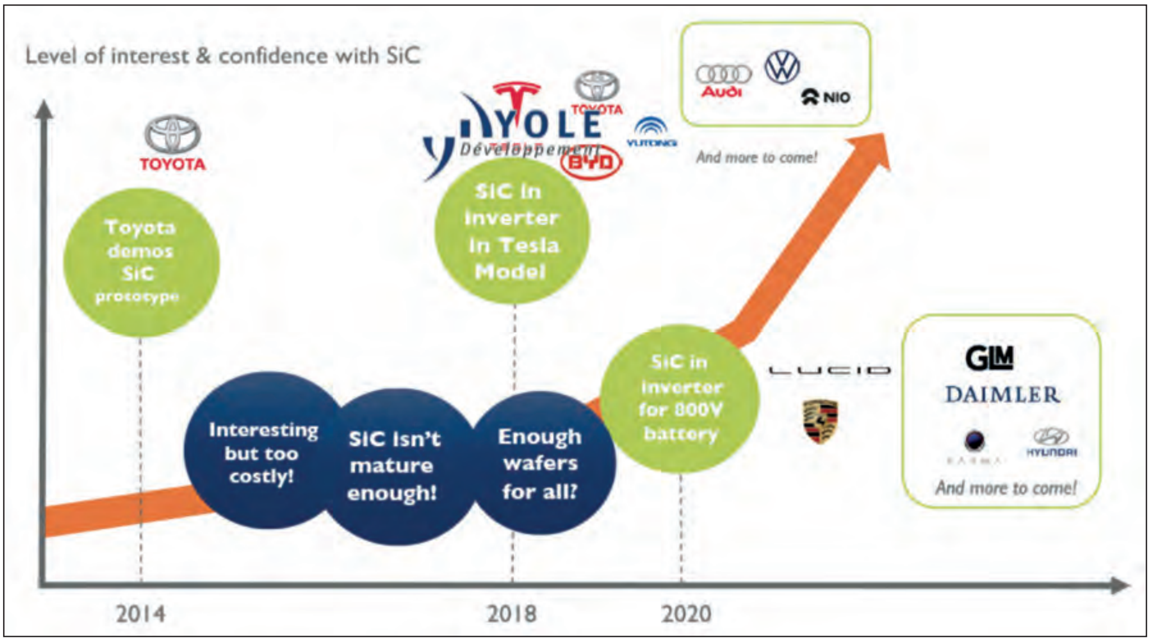


Figure 1: SiC adoption by xEV – Tesla and 800V effects in 2021.

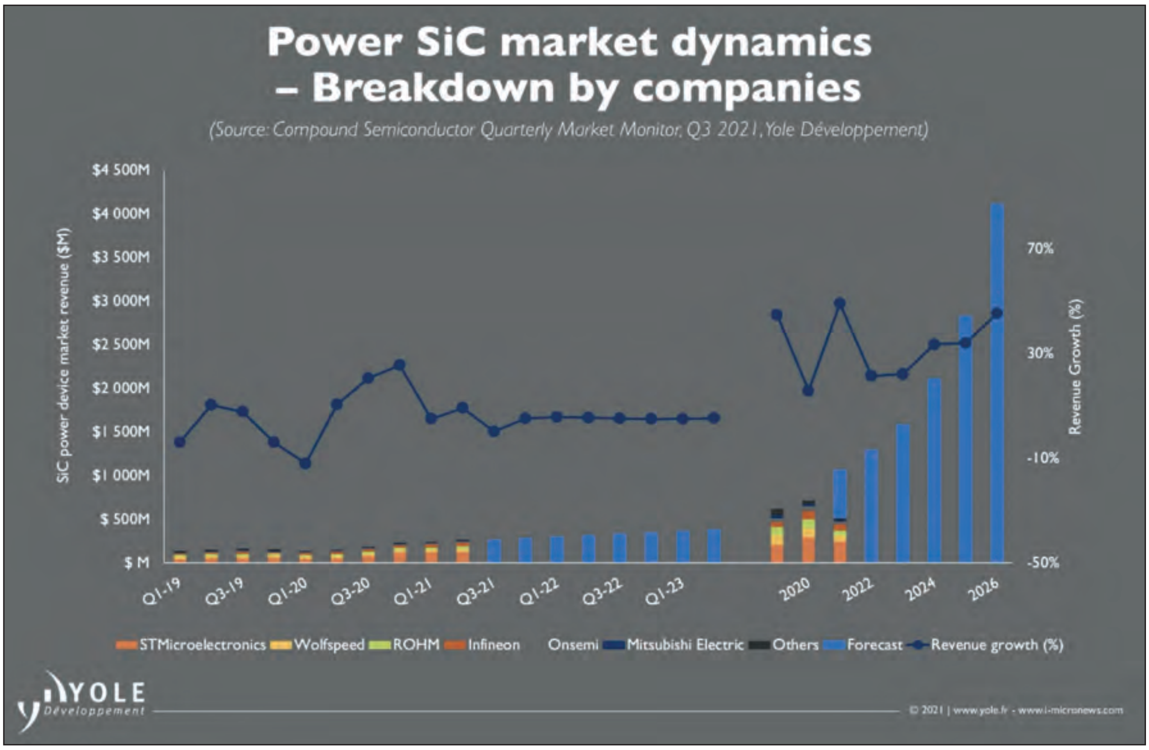


Figure 2: Power SiC market dynamics 2019-2026

and non-EV/HEV players it is worth to follow the EV/HEV trends in order to identify potential opportunities/threats.

EV/HEV charging, energy storage and other markets related to the EV/HEV follow the trends in the EV/HEV industry: increasing EV battery pack voltage (400V/800V) leading to demand for 1,200 V rated power electronic devices, increasing battery cell energy and power densities, increasing battery pack energy capacity resulting in higher charging power needs, implementation of fast-switching silicon carbide (SiC) devices, etc. The companies involved in related applications have to continuously adapt their products while often benefiting of the technology development done for EV/HEVs (figure 1).

Regarding the compound semiconductor industry, the electrification brings new market opportunities for wide band gap materials such as GaN and SiC. In most of the applications from on-board chargers, DC-DC converters and main inverters SiC and GaN are in a tough competition.

The 2018 - 2019 SiC power device market is notable for Tesla's adoption of SiC in its main inverter. Since then, we have witnessed an interest in SiC from almost all carmakers and Tier 1's. While BYD, Toyota, and Hyundai have chosen SiC for their EV models, Audi, GM, Nio, and Volkswagen are expected to follow. We expect that the Silicon carbide (SiC) power modules will also grow fast, with a double digit CAGR in 2020-2026. The total SiC market is expected to go beyond $4B in 2026, and the automotive market will hold more than 60% of total market share.

Concerning GaN, even though its penetration in EV/HEV much slower than expected, there is an increasing interest for DC/DC converters in 48V mild hybrid electric vehicles, which are expected to reach high volume market in next 5 years. In addition, GaN enables an interesting cost and performance for the On-board chargers and DC/DC converters in the electrified vehicles. Players like EPC, Transphorm, GaN Systems, and Texas Instruments have already obtained AEC qualification and the OEMs keep an eye on GaN and develop internally. Recently BMW reached a $100M supply agreement with GaN Systems. Now the question is when and who adopts GaN in the next generation vehicles.

Enkris: Breaking 300 mm barriers

Enkris has demonstrated 300 mm GaN-on-silicon epiwafers for HEMTs – here's how the China epi-foundry super-sized its epitaxy processes, reports **REBECCA POOL**

IN SEPTEMBER THIS YEAR, Enkris Semiconductor claimed a breakthrough when it demonstrated high-quality 300 mm GaN-on-silicon HEMT epiwafers for 200 V, 650 V and 1200 V power applications. In response to industry demand, the China-based pure epi-foundry transferred its 200 mm AlGaN/GaN HEMT epitaxy process to 300 mm silicon substrates, a feat that company chief executive, Kai Cheng, says was a collective effort of both hardware modification and process control.

Enkris had developed its 200 mm process back in 2014. But as Cheng points out: "We decided to move to 300 millimetre following market requests. Thanks to continuous research and development over the years, we transferred our technology to the larger wafer size after we had optimized parts of the process, such as deposition and metrology tools."

Kai Cheng, Enkris CEO

At the heart of Enkris' structures lies a high-crystalline-quality AlN-based nucleation layer onto which aluminium-containing buffer layers are grown to relieve the lattice and thermal expansion mismatches between the silicon substrate and active GaN layers. Thanks to the AlN nucleation layer, Enkris managed to fabricate 300 mm GaN-on-silicon HEMTs with relatively thin buffer layers that meet leakage current requirements whilst keeping overall device costs down.

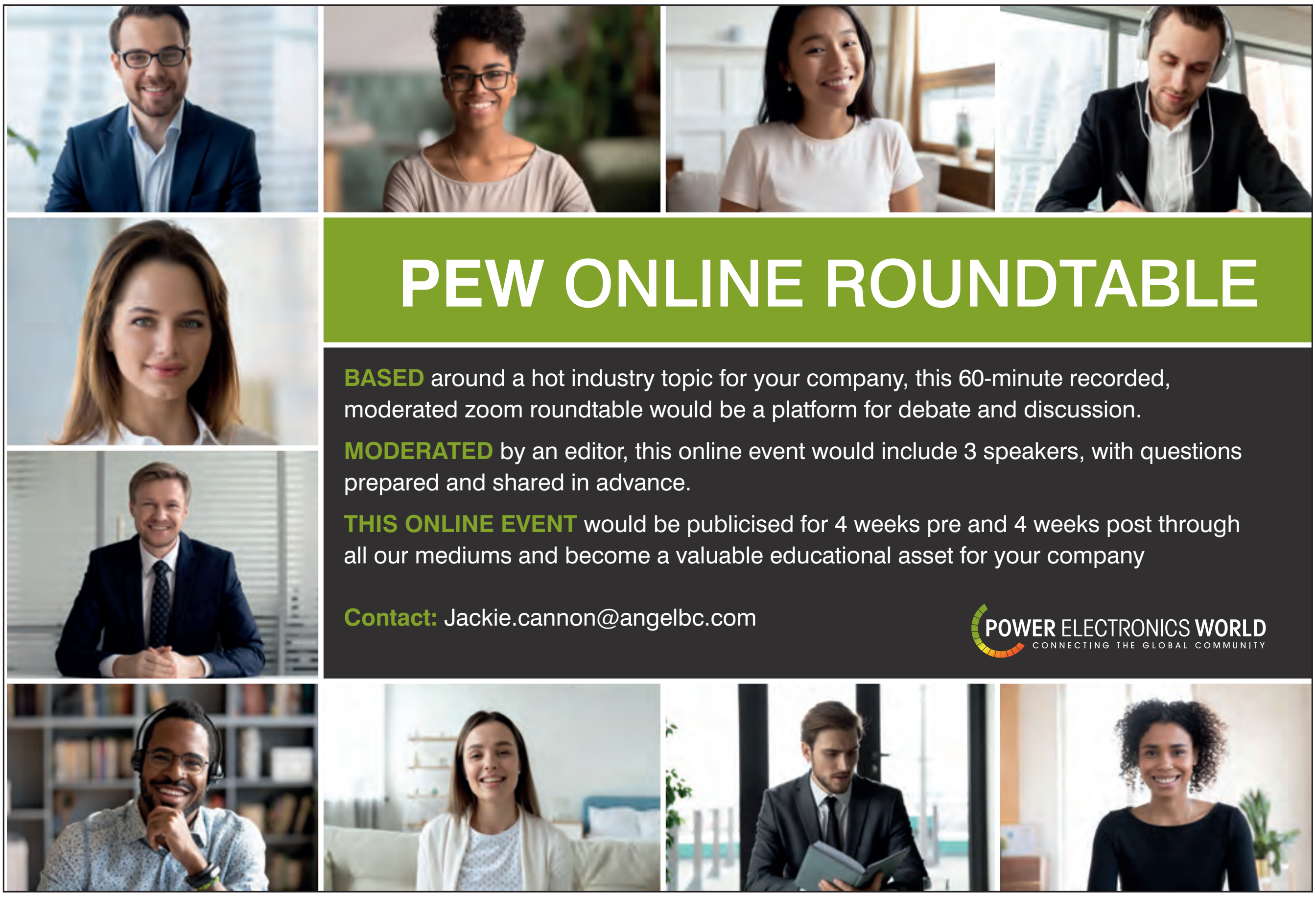
According to Enkris, the buffer layers in its latest epiwafers are only 2-6 μm-thick, have uniform composition across the entire wafer and deliver consistent electrical properties. Company figures indicate wafer bow remains within an acceptable 50 μm while leakage current comes in at 1 μA mm^{-2} at room temperature. As Cheng points out: "Thanks to our aluminium nitride nucleation layer, we have a pretty large process window to manage the stress in thick buffer layers and keep the wafer bow acceptable for the 300 millimetre fab. In addition, the high-quality aluminium nitride also means that defects, such as V-pits and melt-back etching defects at the nitride/silicon interface, are minimized," he adds. "Thus, the leakage current in the vertical direction can be significantly reduced and meet the requirements for high-voltage applications on large-size silicon substrates up to 300 millimetre." Cheng emphasizes that despite the industry-wide challenges associated with epitaxy, strain management and defect control when moving to 300 mm wafer size, his company has achieved excellent structural quality and electrical properties in its AlGaN/GaN HEMT structures. "This will certainly encourage the development of high-power integrated circuits... [and] reduce the cost of gallium nitride power devices," he says. But what about yield figures? It's no secret that poor yields have held back many industry players, keen to work with larger wafers sizes and reap the cost benefits this transition brings.

Cheng is optimistic about yields at 300 mm wafer sizes, but says: "It's still too early to talk about the yields of our twelve-inch wafers in terms of substrates and epitaxy at this moment." Still, as he adds: "We haven't seen any real difficult hurdles of physics yet, but the final yield improvement is dependent on the whole industry's efforts, including metrology tool vendors, processing tool vendors, growers and device makers."

Back in 2014, Enkris also worked closely with Aixtron on its high-voltage GaN HEMT structures on 200 mm silicon, using a high-throughput Crius II Close Coupled Showerhead Reactor. This time around, such system details are not disclosed, but Cheng is certain that devices fabricated from Enkris' 300 mm GaN-on-silicon epiwafers will be cost-competitive. "The gallium nitride-on-silicon wafer costs are generally higher than silicon materials, but gallium nitride materials have very unique properties," he says. "And if we look at silicon power devices, more than three times more gallium nitride devices can be produced from the same wafer size, making the gallium nitride device costs comparable or even lower than its silicon competitors."

So where next for Enkris Semiconductor? Right now, the pure-play epi-foundry is shipping its large size GaN-on-silicon HEMT epiwafers around the world – Cheng says his company is seeing interest from China, the rest of Asia, the US and Europe. He also points out how vertical breakdown measurements indicate the structures can operate at 200 V, 650 V and 1200 V voltage ranges for a wide range of power applications, such as consumer electronics and data-centre applications.

And while Enkris also develops GaN-on-SiC, GaN-on-sapphire and GaN-on-GaN epiwafers, GaN-on-silicon wafers are currently in the greatest demand, being required for RF, power and microLED display applications. "We are growing various interesting structures, but we do pay close attention to customer needs," he says. "As a commercial company, we are creating world-class products for industry."



SiC flexes its green credentials

With ramping levels of chip production and proven green credentials, SiC is well-positioned to play a major role in preventing excessive global warming

BY **RICHARD STEVENSON**

THE DRIVE to net zero cuts both ways. It promises to spur sales of products that cut carbon footprints; but it also heightens the scrutiny that is subjected to anything claimed to curb the rise in the temperature of our planet.

For many years the makers of SiC diodes and transistors have championed the capability of these devices to green our world by deploying them in place of silicon incumbents in electric vehicles, various forms of power supply, solar inverters and power drives for motors. In all these applications making the transition to wide bandgap power electronics trims efficiency losses and paves the way to higher switching frequencies, which in turn allows substantial reductions to the size and weight of electrical units. However, producing SiC devices requires a great deal of energy, in part due to the need for incredibly high temperatures for processing this material. So does SiC really have green credentials? And if it does, is it possible to produce diodes and transistors in volumes that are high enough to actually make a difference?

Providing an emphatic ‘yes’ to both those questions were some of the biggest names in the SiC industry, speaking at this year’s European Conference on SiC and Related Materials (ECSCRM), held from 24-28 October in Tours, France. At that hybrid event John Palmour, CTO of Wolfspeed, delivered compelling evidence for the carbon-cutting capability of SiC power devices, alongside plans to ramp their manufacture; Mario Giuseppe Saggio, SiC Power Devices Design Director at STMicrolectronics, championed the benefits that these devices deliver to electric vehicles, as well as outlining the company’s roadmap for increasing its SiC power portfolio; and Victor Veliadis, Deputy Executive Director and CTO of PowerAmerica, presented an option for cutting the cost of SiC device manufacture.

Gloriously green

Speaking in person at the conference, Palmour presented the results of incredibly rigorous calculations for evaluating the environmental impact of SiC devices. This work, considering the energy of SiC device production from the “cradle to the factory gate”, included factors such as the energy to build and ship production tools and make substrates. When comparing a 400 V silicon IGBT with a SiC MOSFET – these are rivals for deployment in a typical electric vehicle – researchers found that the wide bandgap rival takes about four times as much energy to produce. For this class of MOSFET, requiring 4.75 GJ to make, more than three-quarters of the energy expenditure is associated with the electricity consumed during its productio. However, the savings that come from SiC easily outweigh the additional energy required for its production. For a sedan in EV form, assuming that it covers 200,000 miles over its lifetime – that's a reasonable figure, given that the relatively few moving parts should ensure high reliability – the superiority of SiC over silicon is, in energy terms, a factor of 7:1. And if the EV can operate at 800 V rather than 400 V, this factor climbs to 13:1. Such high returns matter a great deal to the automotive industry, emphasized Palmour, because they allow this sector to get closer to its carbon-neutral target.

Even higher returns on energy expenditure are possible in the solar sector. That's not surprising when considering that cars tend to spend most of their time not being driven, while PV inverters operate for many hours every day. Palmour stated that for a 50 kW system in Albany, the payback would be 55:1, while in the sunnier climes of Phoenix, that figure should hit 77:1.

Further insights into the benefits of using SiC in electric vehicles were provided by Mario Giuseppe Saggio from STMicrolectronics. He pointed out that a typical internal combustion engine has a mass of between 100-250 kg, runs at 250 °C, has an efficiency ranging from 30 percent to 45 percent, and for every kilometre driven, it emits more than 100 g of CO_2. "That's a very large number," pointed out Saggio. In comparison, electrical motors are considerably lighter, operate at 65 °C with an efficiency of more than 90 percent, while emitting no CO_2. Sales of electric vehicles are tipped to climb at a phenomenal rate. Saggio pointed out that one market analyst recently revised its forecast upwards, upping the figure for the compound annual growth rate for the next few years from an already impressive 27 percent to a whopping of 42 percent. Such an astonishing growth rate will help to meet goals for market shares of EVs: in the US and Europe, political leaders have set targets of 50 percent and 37.5 percent by 2030, respectively; while China is aiming for 30 percent by 2025. Moving to far greater electrification of transportation will deliver a tremendous hike in sales of semiconductor devices to automakers. According to analysis quoted by Saggio, the car market was worth $35 billion in 2020, and will soar to more than $70 billion by 2025. Cars with internal combustion engines have a semiconductor content that typically totals $400, while for EVs, this figure tends to top $1000.

Saggio claimed that the motivation for using SiC devices, rather than those made from silicon, is not limited to a higher efficiency. The wide bandgap device also offers a smaller form factor and diminished demand for cooling – SiC has an excellent thermal conductivity, and can handle very high temperatures. For automotive applications, these merits have led to SiC being considered for traction inverters, high-voltage DC-to-DC converters and on-board chargers. While the cost of SiC is higher, with Saggio saying it can be $300 more, analysis by Goldman Sachs suggests that thanks to a higher efficiency, switching from silicon to wide bandgap devices delivers efficiency savings worth around $2000.

When accelerating hard, the power consumed by an EV is very different from when it is coasting along. These variations in load lead to differences in values for efficiency. Saggio compared values for efficiency at different loads, showing that for typical driving conditions, the benefits of SiC over silicon are even greater than at high loads. For many considering whether to buy an EV, a potential deal-breaker is the long charge time. But, in future, it may take no longer to charge a car than fill a tank, suggested Saggio. He spoke of the possibility of a 350 kW fast

The additional energy required to produce SiC devices over those made from silicon is outweighed by the savings that stem from reductions in electrical losses of a PV inverter.

charger, capable of injecting enough energy into a battery in 5 minutes to increase the vehicle's driving range by 250 km. In his view, 800 V devices would suit this application, and could speed adoption of SiC MOSFETs rated at this value or slightly higher.

Incredible expansions

Many of the manufacturers of SiC devices have plans for a massive increase in their production capacity. The roadmap for Wolfspeed is well-publicised, with the building of a large fab in the Mohawk Valley in New York state attracting a lot of publicity.

During Palmour's presentation, he offered an update on the construction of this 484,000 ft^2 fab that will swell the company's production capacity by a factor of 30 compared with 2017. Despite the pandemic, the build is on track, with opening slated for 2022. Initially, Wolfspeed planned to start device production in its new fab on 150 mm substrates, before shifting to 200 mm variants in 2024. But this has changed, with the manufacturer now to use the larger size from the outset. Although there are downsides – currently, the cost-per-unit-area on 200 mm SiC is higher, due in part to an increase in the thickness of the substrate from 350 mm to 500 mm – there are considerable advantages in avoiding having to re-tool two years down the line.

Palmour provided some insights into the progress of Wolfspeed's 200 mm SiC substrates and epiwafers. He shared cross-polarised images of 200 mm SiC substrates, saying that they indicate a very high a structural quality. Dislocation maps reveal basal plane and threading-screw densities of 684 cm^{-2} and 289 cm^{-2}, respectively. Following chemical mechanical polishing, surface quality has been shown to improve, with a Lasertech surface scan revealing no scratches and just 66 defects. Another encouraging result is that trials of epilayer growth in three reactors show that it is possible to realise variations in thickness and doping uniformity that are just over 1 percent. STMicrolectronics is also expanding its SiC production capacity. It is setting up a sister fab in Singapore, with qualification taking place in the final quarter of 2021. For producing its SiC diodes and MOSFETs, this multi-national draws on a combination of its internal production of 150 mm substrates, thanks to the acquisition of Norstel in 2019, and a supply agreement with Wolfspeed for material of that size. STMicrolectronics has interest in 200 mm SiC, and announced this summer that it had demonstrated the fabrication of SiC diodes on this platform.

Production of SiC MOSFETs is well-established at STMicrolectronics, with third-generation products automotive-qualified in late 2020, and a fourth generation underway. Saggio explained that in all these iterations a planar architecture has been favoured over a trench design, because it ensures a simple, very high yield process that is scalable. What's more, this geometry results in a higher channel mobility. With the introduction of each new generation of MOSFET, customers gain access to better devices.

Resistance has fallen from 52 mW to 21 mW and then on to 15 mW with the shift from the second to the third and then the fourth generation of SiC MOSFETs, a move that allows designers to exploit more current for the same die size, or a smaller chip for the same on-resistance. According to Saggio, one of the benefits of replacing a second-generation device with a third-generation equivalent is a trimming of losses by 65 percent. Saggio also took the opportunity during his presentation to warn delegates of a false myth that is perpetuating and threatening to provide a headwind to the phenomenal growth in SiC sales. Rumours are circulating that SiC MOSFETs suffer from reliability issues that are linked to bias threshold instability. However, Saggio said that he has seen no evidence for this. Additional motivation to migrate SiC device production to the 200 mm platform came from Victor Veliadis from PowerAmerica. He claimed that a shift from 150 mm to 200 mm SiC substrates could cut costs by 20 percent. However, to succeed, engineers making this move must increase thickness and doping uniformity.

Veliadis championed the use of silicon fabs for manufacturing SiC devices. He accepts that some new tools are needed that are specific to SiC production. They include equipment used for: dry etching; substrate thinning; ion-implantation doping; and for providing new processes for metallisation, and for the formation of ohmic contacts and a gate oxide with a high-quality interface. According to Veliadis, the total cost for all this equipment is in the range $12-15 million. He believes such an investment is worthwhile, allowing silicon fabs that are "20 years obsolete" to process SiC.

With SiC's green credentials beyond doubt, and COP 26 highlighting that the need to tackle climate change is more pressing than ever, it is good to know that there are plans in place to deliver a tremendous ramp in the production of SiC devices. After all, this rapidly growing multi-billion dollar global industry is going to play a key role in securing the future of our planet.

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Shifting to 200 mm silicon carbide

Introducing larger wafers will accelerate the production of power electronic devices in fully depreciated 200 mm fabs

BY SANTHANARAGHAVAN PARTHASARATHY FROM GT ADVANCED TECHNOLOGIES

THE GOAL of achieving carbon neutrality has gained momentum worldwide. Many steps are being taken to transform our global energy system, including a dramatic reduction in reliance on fossil fuels. The adoption of wide-bandgap semiconductors made from materials like SiC will provide energy-efficient devices that have almost no losses, creating a sustainable path to achieving net zero carbon emission.

Today's power converters, including AC-DC rectifiers, AC-AC transformers, DC-DC converters and DC-AC inverters, tend to employ silicon-based power electronic devices – the IGBT, short for insulated gate bipolar transistor, is among the most commonly used.

However, demands for faster switching frequencies, high power ratings, high conversion efficiencies and high-temperature operation are driving the adoption of devices made from SiC. This wide-bandgap semiconductor combines a bandgap that is three times that of silicon with a thermal conductivity that's also three times higher and a breakdown field that is ten times greater, making devices made from SiC a perfect choice for these operations.

Shipments of SiC power devices, which are made on native single-crystal substrates, have climbed in recent years. This has enabled SiC to move out of the lab and establish itself as a mainstay for power electronic devices, especially when breakdown voltages greater than 900 V are required.

The foundation for commercialization of SiC power devices came in 1999, when 50 mm diameter wafers hit the market, selling for $495 a piece. While that seems an eye-watering price today, at the time this was considered a breakthrough. Now the majority of SiC power electronic devices, such as Schottky barrier diodes, MOSFETs, junction field-effect transistors and cascodes, are built on 150 mm wafers, with fabrication taking place in fully depreciated 150 mm and 200 mm fabs that have become available as wafer sizes in the silicon industry have transitioned to 300 mm.

To provide year-on-year productivity growth in the semiconductor industry, engineers tend to pull on five well-known levers: shrinking device dimensions, introducing a new device design, improving equipment productivity, increasing line yield, and migrating to a larger wafer size. Of these five, the latter offers considerable gains, which is why there is so much interest in the development of 200 mm SiC wafers.

The obvious benefit of increasing the surface area of the wafer is that it drives up the number of devices, or die, that it can yield. This increase diminishes fabrication cost per device, since the number of process steps remains the same (see Table 1).

Readily available fab capacity

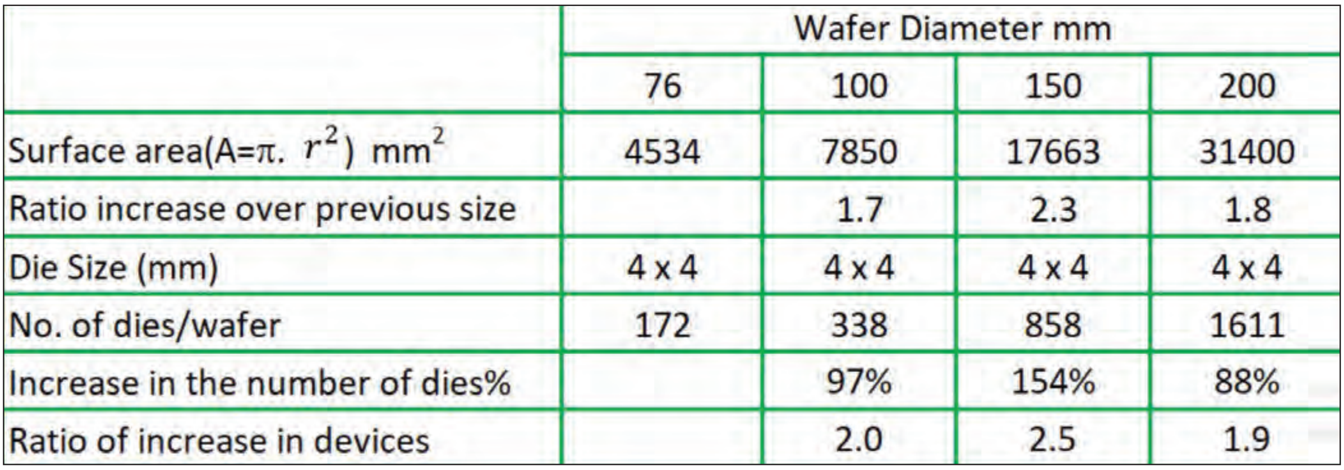
Today silicon-based power devices, such as the IGBT, are mass-produced on 300 mm silicon wafers. That's because Tier 1 integrated device manufacturers (IDMs) have invested billions of dollars over the last few years on 300 mm fabs for making silicon power electronics.

Thanks to the migration of silicon power device manufacturing to 300 mm fabs, fully depreciated 150 mm and 200 mm fabs are now available for SiC production. Supporting this venture, IDMs have added toolsets for SiC device fabrication. These include : MOCVD reactors capable of growth up to 1600 °C; high-energy, high-temperature implanters; dopant-activation furnaces; metrology equipment; wafer-level testing; and die singulation tools. These fabs have enough excess capacity to handle several thousand wafer starts per week.

While Tier 1 IDMs have the benefit of fully depreciated and well-optimized day-to-day run yields aiding competitive manufacturing costs and device prices, it will not be so easy for newcomers with 200 mm fabs. These firms will encounter price pressure and lower yield numbers in the near term.

The introduction of 200 mm substrates is expected to bring down the overall device cost by 20-35 percent relative to production on a 150 mm platform. This can occur even if there is an increase in material costs at the wafer level. For the ease of achieving good wafer geometry, there is an increase in wafer thickness as the wafer diameter grows. 150 mm-diameter SiC wafers have a thickness of 350 μm, and the initial 200 mm SiC substrates introduced to the market will be 500 μm-thick. As increased thickness reduces the number of wafers made from each puck, there is a slight rise in wafer cost. However, the increased thickness helps to ensure a good wafer geometry, while minimizing bow and warp.

Even with today's fabrication tooling capabilities, it is possible to produce 350 μm-thick 200 mm



	Wafer Diameter mm			
	76	100	150	200
Surface area(A=π. r^2) mm^2	4534	7850	17663	31400
Ratio increase over previous size		1.7	2.3	1.8
Die Size (mm)	4 x 4	4 x 4	4 x 4	4 x 4
No. of dies/wafer	172	338	858	1611
Increase in the number of dies%		97%	154%	88%
Ratio of increase in devices		2.0	2.5	1.9

Table 1. The number of die increase with wafer size.

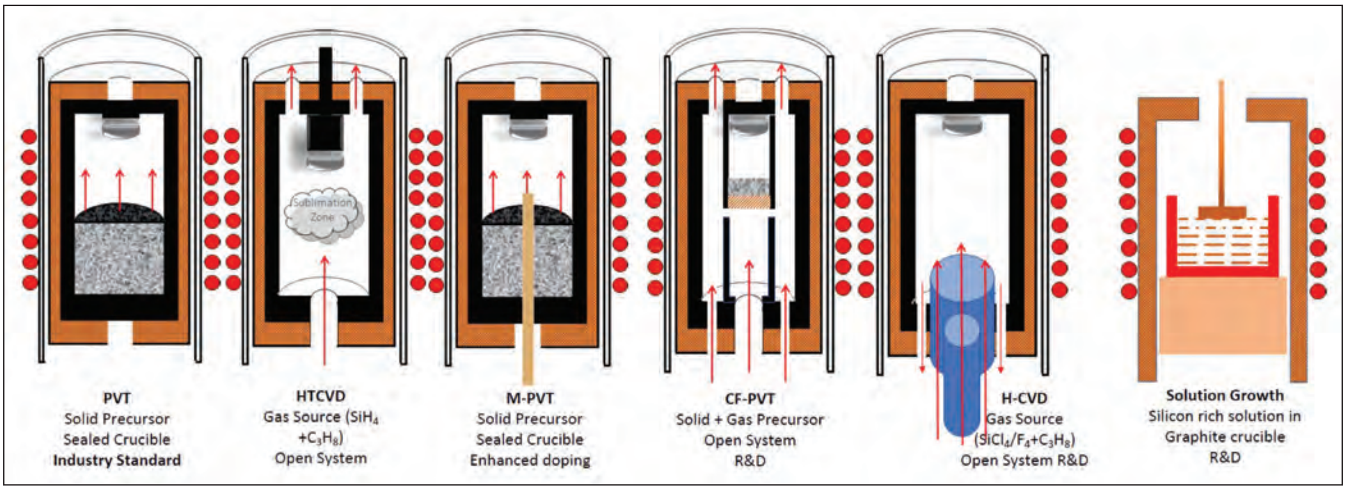


Figure 1. There are several different techniques for producing bulk SiC.

wafers that would provide an additional reduction to substrate costs. However, that's not an essential step, as irrespective of wafer thickness, SiC wafers with a 200 mm diameter offer reduced device costs compared with their 150 mm siblings.

While moves to larger substrate sizes over the past two decades have helped to cut production costs for SiC devices, they are still about three times higher than those of silicon variants. That's not a showstopper, though, because when a circuit designer switches from silicon devices to those made from SiC, they get a 5-10 percent cost reduction at the system level. The introduction of 200 mm SiC wafers will amplify this benefit and lead to further falls in overall system-level cost over the next few years.

Scaling challenges

For elemental semiconductor materials such as silicon and germanium, as well as compound semiconductor materials such as GaAs and InP, crystalline material is grown from the melt. Crystal growers begin by taking a seed crystal, with a cross-section typically 10 mm by 10 mm, and use the thin neck created between the seed and the melt interface to increase the diameter of the crystal to the required level. Once this is established, the crystal is pulled out of the melt at a rate that depends on the material. This rate ranges from 1 mm/hour to 150 mm/hour.

One of the biggest downsides of SiC is that the material doesn't exist in a liquid phase, so crystals can't be grown from a melt. If SiC is held at a high temperature and low pressure, it dissociates into gaseous species without passing through the liquid phase. Due to this behaviour, SiC crystals are grown using a vapour phase technique called sublimation, or physical vapour transport (PVT). For growing material using this method, an essential ingredient is a seed crystal with a diameter similar to that of the boule (read on to discover how the seeds are expanded). With PVT, growth rates are in the range of 0.1-0.5 mm/hour.

To take the quality of SiC to a new high, and to enable a more precise control of the growth of this material, researchers have realized additional advances to the PVT process, and explored other viable options (see Figure 1). One refinement, adopted by industry, is the use of gaseous cracking to supply the carbon and silicon, rather than a solid SiC powder. This technique

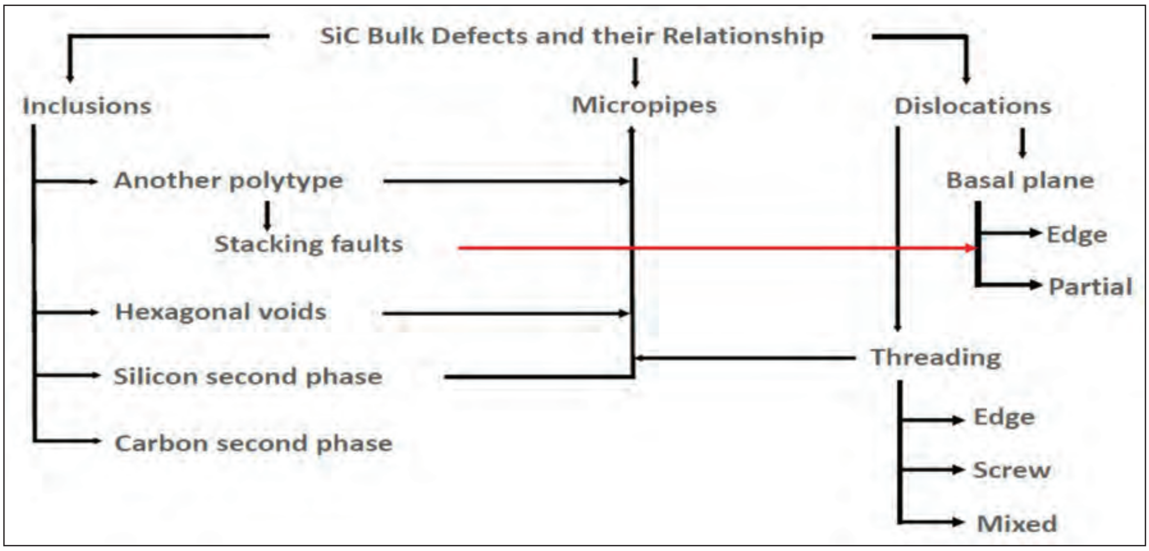


Figure 2. Various defects observed in bulk SiC and their relationship.

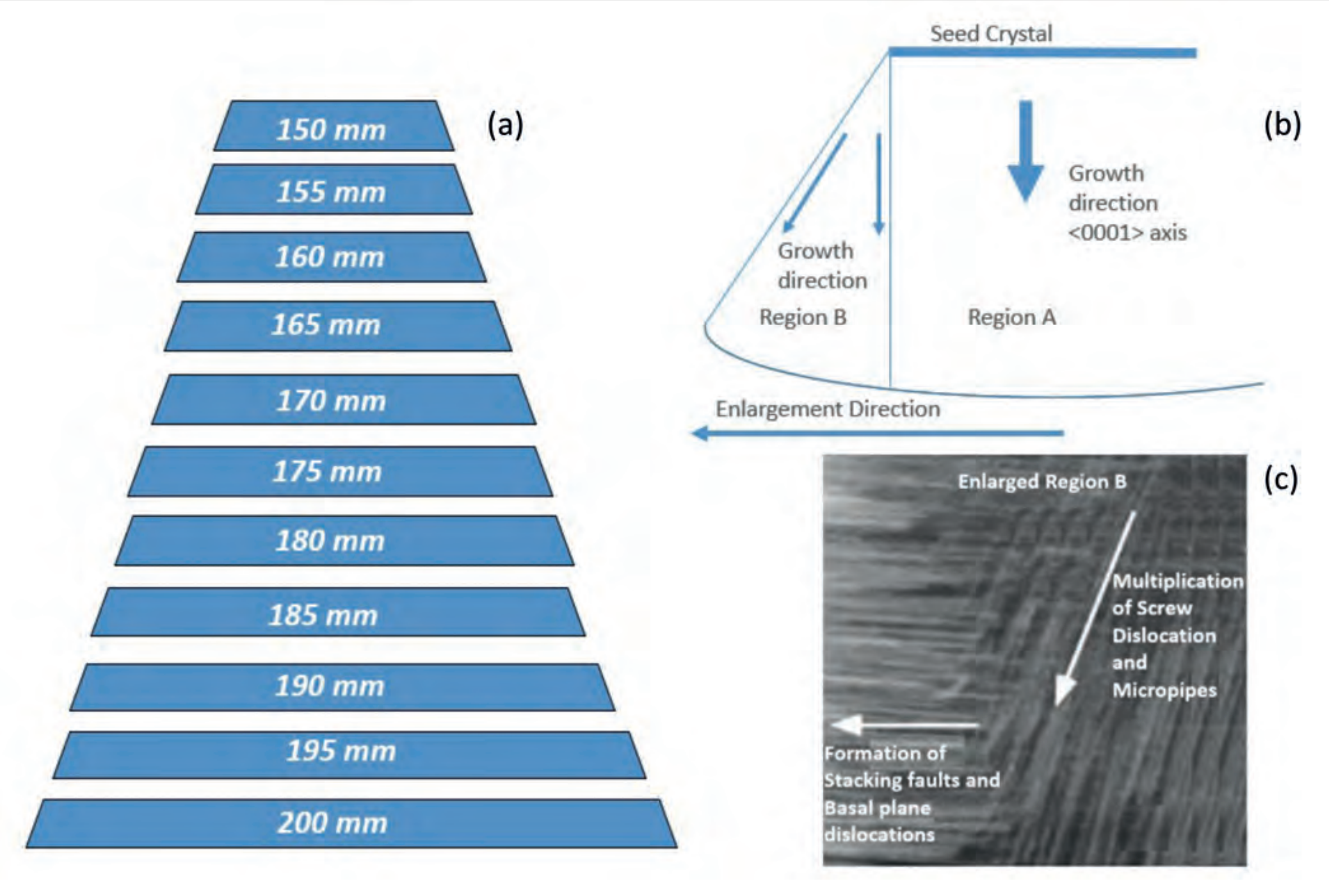


Figure 3. Seed enlargement lies at the heart of the introduction of larger wafer sizes. Shown here are illustrations of: (a) a seed expansion process from 150-200 mm, and (b), the defects that can develop during the seed expansion process. The newly expanded region is susceptible to the formation of more defects (c).

is called high-temperature chemical vapour deposition (HT-CVD).

Another alternative is modified PVT (M-PVT), an approach that incorporates an additional feed tube into the growth zone for the dopant gas, which could be nitrogen or other materials. This modification enables the production of low-resistivity SiC with uniform resistivity profiles. Using conventional PVT, one downside is that the dopant gas is introduced outside the growth zone. This prevents the production of low-resistivity material with good uniformity, due to limited diffusion.

At the research level, other techniques are being explored for the growth of crystalline SiC. These methods, which are a long way off producing commercial-scale SiC wafers, include halide CVD, as well as a combination of HT-CVD and PVT that is known as continuous-feed PVT.

Recently, there has been interest in the growth of bulk SiC from solution, as this has the potential for producing large-sized, high-quality SiC wafers. But this technique, still being researched, is not yet capable of achieving commercialization. One of its drawbacks is that due to the lack of a stoichiometric SiC liquid phase at atmospheric pressure, it is impossible to employ congruent melt growth. Another downside is that the solubility of carbon in molten silicon is very limited at very high temperatures. It is possible to enhance the solubility of carbon by turning to solvents, such as Ti-Si, Al-Si, Cr-Si, Fe-Si, Si-Sc, Si-Co, Sn-Si and Si-Ge. However, these solvents threaten to be incorporated in the grown crystal matrix. Another issue is that the growth of larger crystals is not sustainable with these methods.

Due to the considerations surrounding the growth of SiC by a variety of methods, today almost all commercially grown SiC crystals are produced by PVT. With this approach, PVT furnaces are either inductively or resistively heated.

Crystal characteristics

SiC can be crystallized in three crystal structures: cubic (C), hexagonal (H) and rhombohedral (R). Variations of this material are far greater than these three, however, with SiC exhibiting more than 220 polytypes. These differ in how they occupy sites along the *c*-axis, with classification of the polytype depending on the number of Si-C layers in the unit cell. For power electronic applications, the best polytype is 4H SiC.

Difficulties inherent to vapour phase growth give rise to a variety of defects, including micropipes, screw dislocations, edge dislocations, stacking faults, inclusions, and partial and mixed dislocations. Device performance is impaired by micropipes, screw dislocations and basal planar defects. However, the density of these imperfections can be reduced during crystal growth and subsequent epilayer deposition, which takes place prior to front-end processing. The relationship between the different defects in SiC is illustrated in Figure 2.

During the past twenty years, manufacturers of SiC have taken a step-by-step approach to expanding seed sizes. Progress is not easy, as this expansion is a time-consuming, iterative process, involving several cycles of learning and process optimization. The starting point for seed development dates back to the 1990s, with the formation of self-nucleated Lely platelets with a 4 mm by 4 mm cross-section. These days, efforts are directed towards expanding seeds from 150 mm to 200 mm, a challenging task given that the newly expanded region is susceptible to the formation of more defects (see Figure 3).

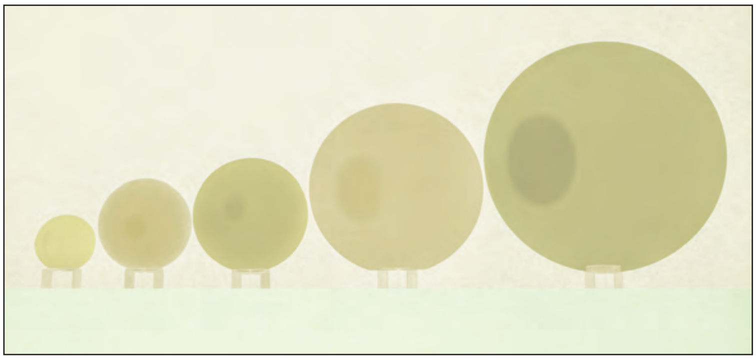


Figure 4. GTAT's progress in crystal growth from 50 mm to 200 mm.

Success in expanding seed dimensions demands a concurrent undertaking of several iterations of thermal and crystal growth computation, fluid dynamics and numerical modelling in a virtual platform, and hot zone design optimization for larger seed sizes. To preserve the quality of the crystal in the starting seed, there is a need to control the advancement of the solid-gas interface and maintain the shape of the growth interface via careful selection of axial and radial temperature gradients.

Evaluating economics

With the growth rate for 200 mm SiC crystals almost the same as that for their 150 mm siblings, there is no appreciable increase in the production cycle time, allowing equipment throughput to be maintained. Costs do rise slightly, however, due to an increase in the expense of hot-zone components, stemming from an increase in the size of this part in the growth chamber. Fortunately, there have been recent advances in graphite manufacturing, as well as a far better understanding of how to tune the growth process. Due to these gains, it is now viable to make cost-effective hot-zone components for 200 mm crystal growth, and if higher volumes are used, expenditure diminishes. Working in this manner, our team at GT Advanced Technologies (GTAT) has developed the SiClone 200 platform, which is capable of producing 150 mm and 200 mm diameter crystals without additional capex.

As well as crystal growth, seed/wafer fabrication involves outer diameter grinding, flat grinding, wafering, lapping and polishing – and each process needs to be optimized as the wafer diameter increases. There are already productivity increases at the wafering step, accomplished by reducing kerf loss during the slicing process. Traditionally, slicing SiC wafers involves multi-wire saws and diamond slurry, and leads to a kerf loss below 200 μm and a grinding loss of less than 100 μm, required for removal of sub-surface damage. Introducing laser-based slicing trims total material losses for wafer processing by one-third, to around 100 μm.

At the fab level, cost increases associated with migrating to 200 mm are minimal. Offsetting the relatively low add-on costs for 200 mm SiC crystal growth and wafer manufacturing is an increase in the number of dies per wafer. This makes the switch, which will deliver significant dividends in the power electronic industry, profitable and sustainable. Today's epi-ready 150 mm SiC wafers retail for $750-$900, and 200 mm wafers are expected to be priced at $1300-$1800. At GTAT, we have a roadmap to reduce costs even further.

Our company has a rich heritage as a manufacturer of crystal growth furnaces, with a global installed base of thousands of systems, and a strong track record in increasing wafer diameters (see Figure 4). Our know-how in equipment design, process scaling, facility planning, and the supply chain helps us to ramp SiC capacity faster, while competing successfully on price and quality. We are now in a position to push forward with 200 mm SiC, thanks to our continuous improvement, grounded in increased cycles of learning and optimization, along with R&D efforts. Our 200 mm product launch is slated for late 2021/early 2022.

If SiC continues to follow in the footsteps of the silicon industry, the next wafer size could be 300 mm. According to our initial thermal modelling, implementing unique hot-zone design components could minimize the applied shear stress, which is responsible for generating dislocations and micropipes, along with the von Mises stress that is to blame for boule cracking. If, further down the line, the industry seeks a 300 mm SiC wafer to reduce costs, we are confident in our ability to develop that next-generation crystal.

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REDEXPERT

Targeting medium-voltage power electronics with vertical GaN devices

Vertical GaN *p-n* diodes combine excellent efficiencies with incredibly fast protection from unwanted electromagnetic pulses

BY ROBERT KAPLAR FROM SANDIA NATIONAL LABORATORIES, TRAVIS ANDERSON FROM THE NAVAL RESEARCH LABORATORY, SRABANTI CHOWDHURY FROM STANFORD UNIVERSITY AND OZGUR AKTAS FROM EDYNX

WE ARE LIVING in an age of increased awareness of energy efficiency. This is partly caused by concerns over global warming, rammed home by alarming images of this year's floods and heat waves. However, it also comes from increasing use of battery power, particularly in transportation, and the need to make the most out of this stored energy.

For the electric grid and various microgrids, demand is on the rise for high-efficiency solid-state power conversion in the medium-voltage range, which roughly spans 1.2 kV to 20 kV. Power converters operating in this domain could serve in solid-state transformers operating at the grid distribution-level, such as those at 13.8 kV, as well as DC microgrids, including those proposed for all-electric aircraft at 10 kV.

Thanks primarily to a breakdown electric field that is far higher than that of silicon, wide-bandgap semiconductors, such as SiC and GaN, offer outstanding opportunities for improving medium-voltage power electronics. As well as reducing on-resistance, they can increase conversion efficiency and slash system size, due to higher switching frequencies. Of the two successors, GaN may ultimately have the upper hand at voltages of 10 kV and more, due to its higher electron mobility (see Figure 1).

The results shown in Figure 1 compare the performance of a type of GaN vertical power transistor known as a CAVET – its full name is a Current-Aperture Vertical-Electron Transistor – with a SiC MOSFET. Note, however, that the trend is applicable to other types of vertical power device. The term 'vertical' is used for device architectures that contain a thick, low-doped drift region. This layer provides the blocking voltage and governs the on-resistance of the device.

As the operating voltage increases, the efficiency of the GaN converter improves relative to that of SiC (this can be seen by comparing the performance of 1.2 kV and 8 kV devices). At first glance, the increase is trivial, but this overlooks the need to consider the difference from 100 percent efficiency. Evaluated in this manner, which hones in on the loss, the difference is substantial.

One major downside of vertical GaN devices is that they are not as mature as their SiC cousins, and in this regard, in a different league from those made from silicon. To fully evaluate the feasibility of vertical GaN there needs to be ongoing improvements in the epitaxial growth of GaN on its native substrate, as well as advances in device processing, such as those that enable effective edge-termination structures.

To this end, our US collaboration, led by researchers at Sandia National Labs and involving engineers at the Naval Research Laboratory, Stanford University, Edynx, and Sonrisa Research, has established a vertical GaN foundry that is targeting 1.2 kV, 3.3 kV, and 6.5 kV devices. This holistic effort combines epitaxial growth with wafer metrology, device design, processing and characterization – the latter includes investigation of yield, reliability testing, and failure analysis.

We are also undertaking a parallel effort that is focusing on higher-voltage structures, eventually up to 20 kV, and targeting specialized devices with a very fast breakdown that are capable of protecting the electric grid from electromagnetic pulses.

We have undertaken extensive mapping of bare GaN substrates and epiwafers with GaN *p-n* diode structures grown by MOCVD. Tools for this mapping include an optical profiling system, Raman spectroscopy, and typical mercury probe. The profiling system's capabilities are illustrated in Figure 2, which has maps of three 2-inch wafers featuring 8 μm, 10 μm and 12 μm-thick drift layers with a net doping density of 1.3×10^{16} cm^{-3}. For our foundry effort, we tend to use such structures for fabricating 1.2 kV devices.

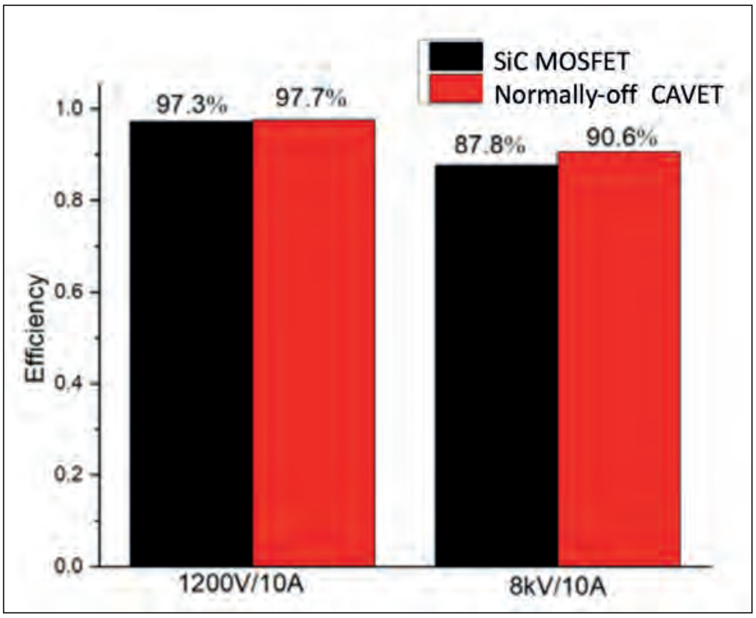

Figure 1. Simulated switching efficiency improvement for vertical GaN CAVETs (a type of vertical transistor) compared with SiC MOSFETs at 1.2 kV and 8 kV. Mobilities of 950 cm^2 V^{-1} s^{-1} and 1200 cm^2 V^{-1} s^{-1} are used for SiC and GaN, respectively (taken from D. Ji *et al*. Int. J. High-Speed Elec. Sys. **28(01n02)** 1940010 (2019)).

Fabrication of our devices occurs at the 2-inch wafer scale, using a foundry environment at the US Naval Research Laboratory. Here, standard processing techniques for III-N devices realize contacts, isolation, and so on.

Evaluating edge termination

When producing these GaN diodes, the most critical process step is edge termination, which is realized by ion implantation. Although etch-based processes have been shown to achieve high performance, we employ implantation for the foundry, because this enables a planar process that is compatible with true foundry manufacturing. Using ion implantation, we have processed epitaxial wafers into devices with various combinations of junction termination extensions and guard rings (see Figure 3 for photos of typical GaN foundry wafers and associated forward current-voltage characteristics). Measurements on our diodes reveal excellent turn-on behaviour and electroluminescence typical of a GaN *p-n* junction.

For diodes with areas ranging from 0.1 mm^2 to 1.0 mm^2, forward current capability is more than 5 A, corresponding to current densities spanning 500 A cm^{-2} to 5000 A cm^{-2}. The related specific on-resistance is 0.3 mΩ-cm^2 to 1.2 mΩ-cm^2.

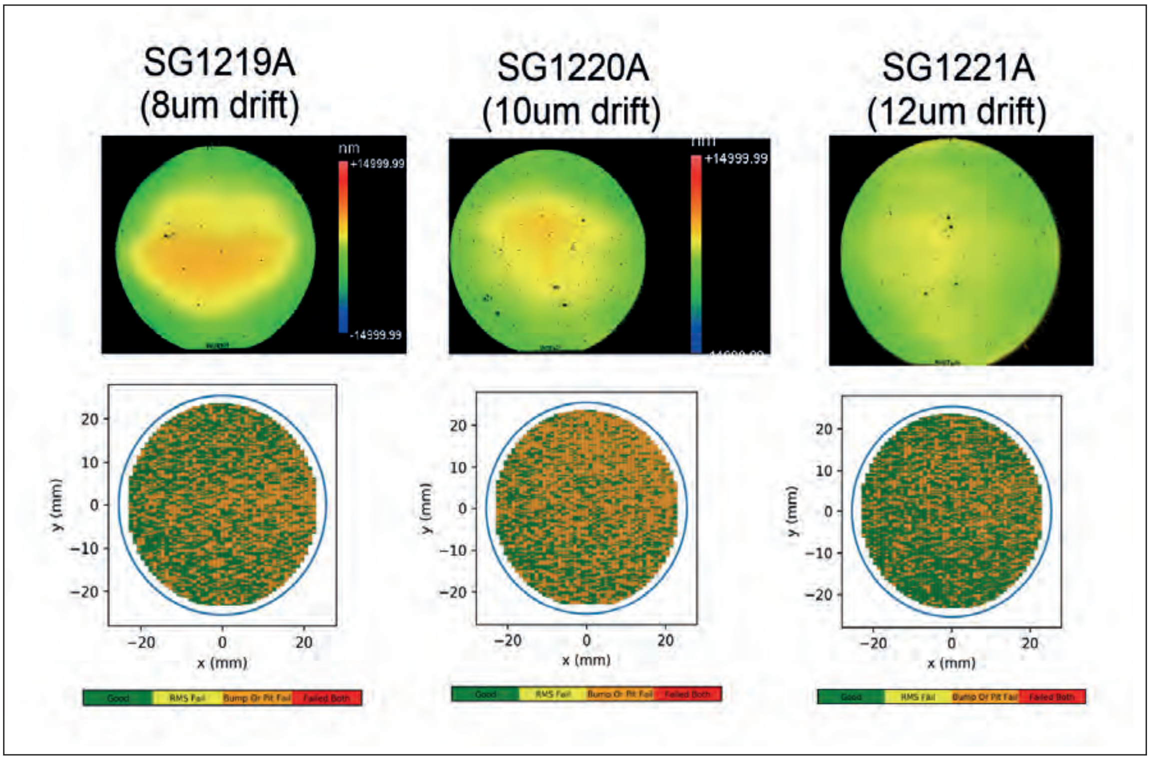

Figure 2. Optical profiles of 2-inch diameter GaN substrates with 8 μm, 10 μm, and 12 μ m drift regions grown by MOCVD. The top portion of the figure shows the raw data, while the bottom portion shows yield maps: green indicates a good device; yellow a failure due to root-mean-square (RMS) roughness; orange a failure due to a bump or pit; and red a failure due to both modes.

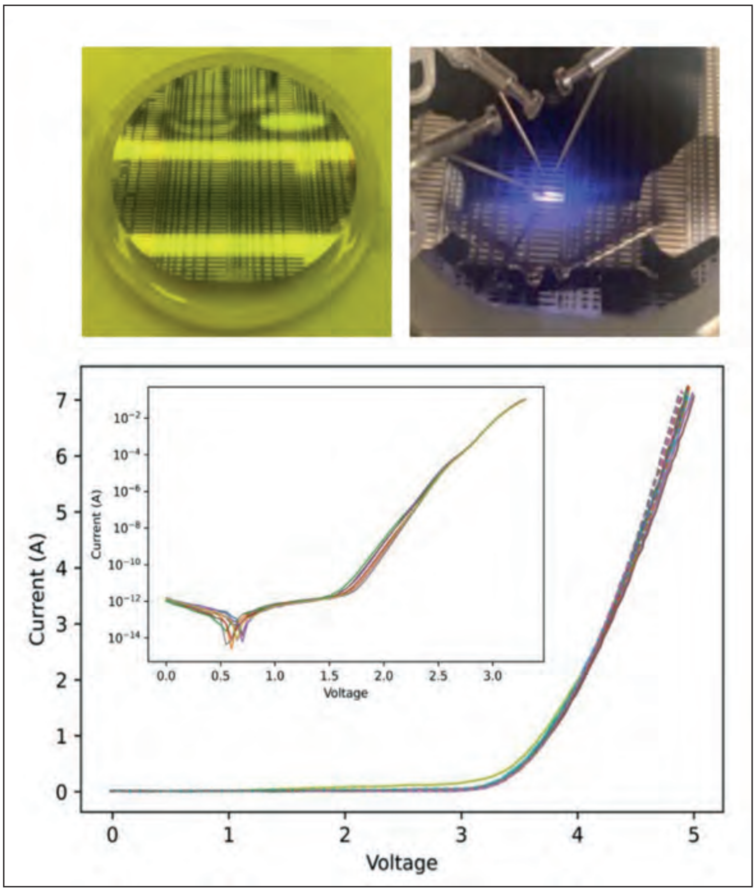

Figure 3. A photo of a typical GaN *p-n* diode foundry wafer (top left), and such a wafer under test (top right), with visible sub-bandgap light emission. The bottom portion of the figure shows representative forward current-voltage curves (main figure, linear scale; inset, log scale).

We have also assessed the breakdown voltage of our devices. Sampling twelve of them from a single wafer shows that the breakdown voltages exceeds 1.3 kV in all cases – this is approximately 90 percent of the theoretical parallel-plane limit. Note that the precise nature of the breakdown depends on the details of the edge termination. Devices receiving a shallower termination implant profile exhibit a breakdown indicative of avalanche behaviour and characterized by an abrupt increase in current.

We are also exploring other approaches to edge termination. They include a bevel design, which we have evaluated with extensive numerical simulations (one example is shown in Figure 4, with results for a 5° bevel). One key finding of this work is the need for very small bevel angles, employed to ensure that the electric field at the edge of the structure is maintained below the ideal parallel-plane maximum electric field (it is around 3.1 MV/cm for the case shown). We have drawn on the results of simulations to guide our fabrication of bevel-terminated diodes, using either a flowed photoresist for bevel angles of 5°, 15°, and 50°, or greyscale lithography for a bevel angle of 1°.

With vertical GaN power devices at an early stage of development, it is not surprising that reliability studies are relatively rare. Our team is adding to them, using high-temperature operating life tests to assess the diode forward-current stability, and evaluating reverse-current stability with high-temperature reverse-bias testing. In both cases, test conditions are carefully monitored to ensure that the device's temperature and its bias stay constant throughout this test.

One key finding of these investigations is that there is a significant increase in the forward current during high-temperature operating life testing. Another important observation is that when the diode is biased in the avalanche region, there is a change in the avalanche current during high-temperature reverse-bias testing. Thermal considerations limit the DC avalanche current, which exhibits a thermal transient during the first minute at elevated temperatures.

Our team has also conducted failure analysis on selected failed devices. This includes inspecting a diode that failed high-temperature reverse-bias testing with emission microscopy (see Figure 5). Using this technique, we observed that the emission is near the edge termination of the device, indicating that this portion of the diode is responsible for its failure.

Protecting the grid

Electromagnetic pulses pose a significant threat to the electric grid, as they could potentially cause blackouts over an extremely large geographical area. For electromagnetic pulses with transients shorter than a microsecond, over-voltage conditions that ensue could cause damage to today's grid. One solution is to introduce fast breakdown GaN *p-n* diodes – they are capable of clamping the voltage across equipment on the grid when it is subjected to such pulses.

A target voltage for this specialized but critical application is 20 kV. This blocking voltage provides an adequate margin for protecting, with a single device, distribution-level equipment, when typically operating at up to 13 kV; and it provides a building-block for protecting sub-transmission equipment, as only a small number of stacked devices are needed to reach 69 kV, a typical requirement for this application.

We have started on the path to producing 20 kV devices, with efforts to date focusing on '5 kV class'

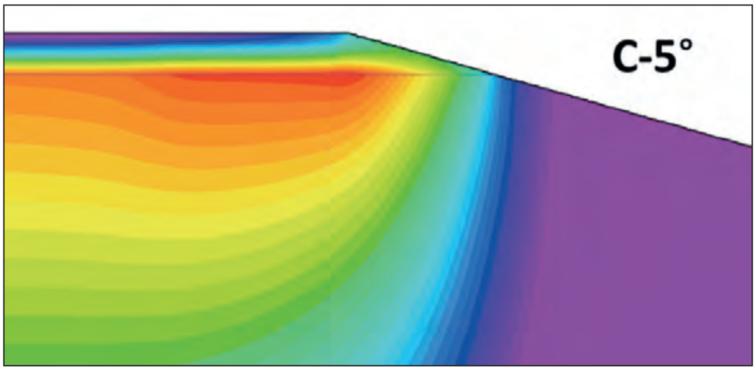

Figure 4. Electric field magnitude for a 5° bevel termination with an 8 μm-thick drift region with a net *n*-type doping of 1.3×10^{16} cm^{-3} and a 500 nm-thick anode layer with a magnesium concentration of 3×10^{17} cm^{-3} to achieve *p*-type doping.

Figure 5. Left image shows an emission microscopy image of a GaN *p-n* diode at 1 kV and 0.5 mA under 2.5x magnification. A single emission spot is visible at the corner of the device at the termination of the junction-termination extension. Right image shows expanded view of the emission spot.

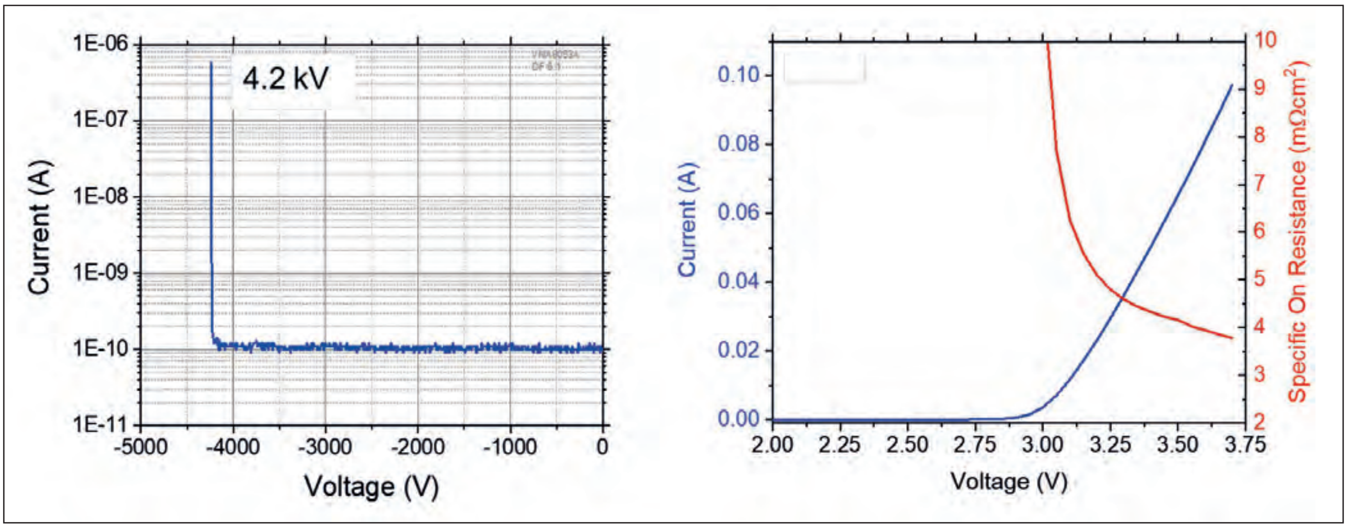

Figure 6. Current-voltage characteristics of GaN *p-n* diodes with 45 μm-thick drift regions intended for an electromagnetic pulse arrestor. Left panel shows low reverse-bias leakage current and breakdown around 4.2 kV; and right panel shows forward-bias current and differential specific on-resistance, which is approximately 3.8 mΩ cm^2 at 3.75 V.

While vertical GaN power devices hold promise for medium-voltage power electronics, challenges must still be overcome related to substrates, epitaxial materials growth, and device processing. Additionally, there is a need to characterise and understand yield and reliability, to enable the fabrication process to become commercially viable

GaN *p-n* diodes. These devices have an epitaxial structure that consists of a 45 µm-thick drift region with a net *n*-type doping in the $2\text{-}5\times10^{15}$ cm^{-3} range. Like the foundry diodes, the structure has been grown by MOCVD. The anode design contains a two-layer *p*-region with a *p*-minus layer (magnesium level of around 1×10^{18} cm^{-3}) near the junction and a higher *p*-doped layer (magnesium level of around 3×10^{19} cm^{-3}) on top. After epitaxial growth, wafers are processed using a multi-step junction-termination flow, using sequential BCl_3/Cl_2 inductively coupled plasma etches.

Electrical measurements of a representative 150 µm-diameter diode reveal that it is extremely well-behaved under reverse bias, exhibiting a low leakage current until the onset of abrupt breakdown at around 4.2 kV (see Figure 6). When operated under forward bias at 3.75 V, the diode shows good turn-on and a differential specific on-resistance of 3.8 mΩ-cm^2, calculated when defining the area as that of the *p*-contact.

To assess the capability of these diodes for electromagnetic pulse protection, we measured response times with a transmission-line system. This approach, drawing on a setup previously used to measure the reverse-recovery time of GaN *p-n* diodes, provides an upper bound of 1.3 ns for the time to breakdown. This incredibly short time demonstrates that this diode can arrest the fast component of an electromagnetic pulse.

REFERENCES

- I. C. Kizilyalli *et al*. "Vertical Power PN Diodes Based on Bulk GaN," IEEE Trans. Elec. Dev. **62** 414 (2015)
- D. Ji *et al*. "On the Progress Made in GaN Vertical Device Technology – Special Issue on Wide Band Gap Semiconductor Electronics and Devices," Int. J. High-Speed Elec. Sys. **28(01n02)** 1940010 (2019)
- I. C. Kizilyalli *et al*. "Reliability Studies of Vertical GaN Devices Based on Bulk GaN Substrates," Microelec. Rel. **55** 1654 (2015)
- J. S. Foster Jr. *et al*., "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack: Critical National Infrastructures," Defense Technical Information Center (2008)
- D. Mauch *et al*. "Ultrafast Reverse Recovery Time Measurement for Wide-Bandgap Diodes," IEEE Trans. Power Elec. **32** 9333 (2017)

While vertical GaN power devices hold promise for medium-voltage power electronics, challenges must still be overcome related to substrates, epitaxial materials growth, and device processing.

Additionally, there is a need to characterise and understand yield and reliability, to enable the fabrication process to become commercially viable. Our team is examining these issues as we establish a foundry for fabricating vertical GaN *p-n* diodes.

Additionally, we are pursuing specialized applications, such as electromagnetic pulse protection, that utilize the diodes' fast breakdown response. Further research will determine the full extent of the capabilities of vertical GaN power devices.

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Your personalised connector

With its WE Plus option, Würth Elektronik offers you terminal blocks in individually customised formats. The range of possible customizations makes these products exceptionally versatile. For example, you can avoid wiring errors by having us print connectors with coding. Terminal blocks with a tension clamp system, for instance, are available in customized colour codes. Coding and changing the pitch by removing pins is equally as achievable as mounting additional coding pins.

Würth Elektronik assembles modular terminal blocks with special pole numbers according to your exact specifications.

And you don't have to wait long for this. As the customisations are based on our standard stock items, we can offer short delivery times. Don't forget, Würth Elektronik is also your ideal partner for small quantities – perfect for prototype and pre-production projects.

Find out more about Terminal Blocks from Würth Elektronik on the WE Plus-Page.

Customised terminal blocks

Are you moving into high volume production and need a custom solution? We have experienced product developers, in-house tooling and the ability to adapt our manufacturing machinery and equipment to design and produce a customised product specifically for you. When we promise 'tailored to your needs', it includes our knowledge, products and production processes.

Talk to our electromechanical specialists.
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