PEW
POWER ELECTRONICS WORLD
CONNECTING THE GLOBAL COMMUNITY

HOW TO UNLEASH GaN POWER SAVINGS

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INSIDE

News Review, Features
News Analysis, Profiles
Research Review
and much more...

GaN blossoms into full technology solution

GaN devices, are becoming more and more available targeting an ever-increasing range of applications

Automation in new power electronics reliability

Test automation is critical for optimizing reliability testing of semiconductor devices during all stages from R&D to manufacturing

Silicon-based semiconductors: powering ahead

MOSFETs and IGBTs, are essential in every modern power electronics system and play a crucial role in converting electrical energy

VIEWPOINT

By Phil Alsop Editor

EVs – charging ahead?

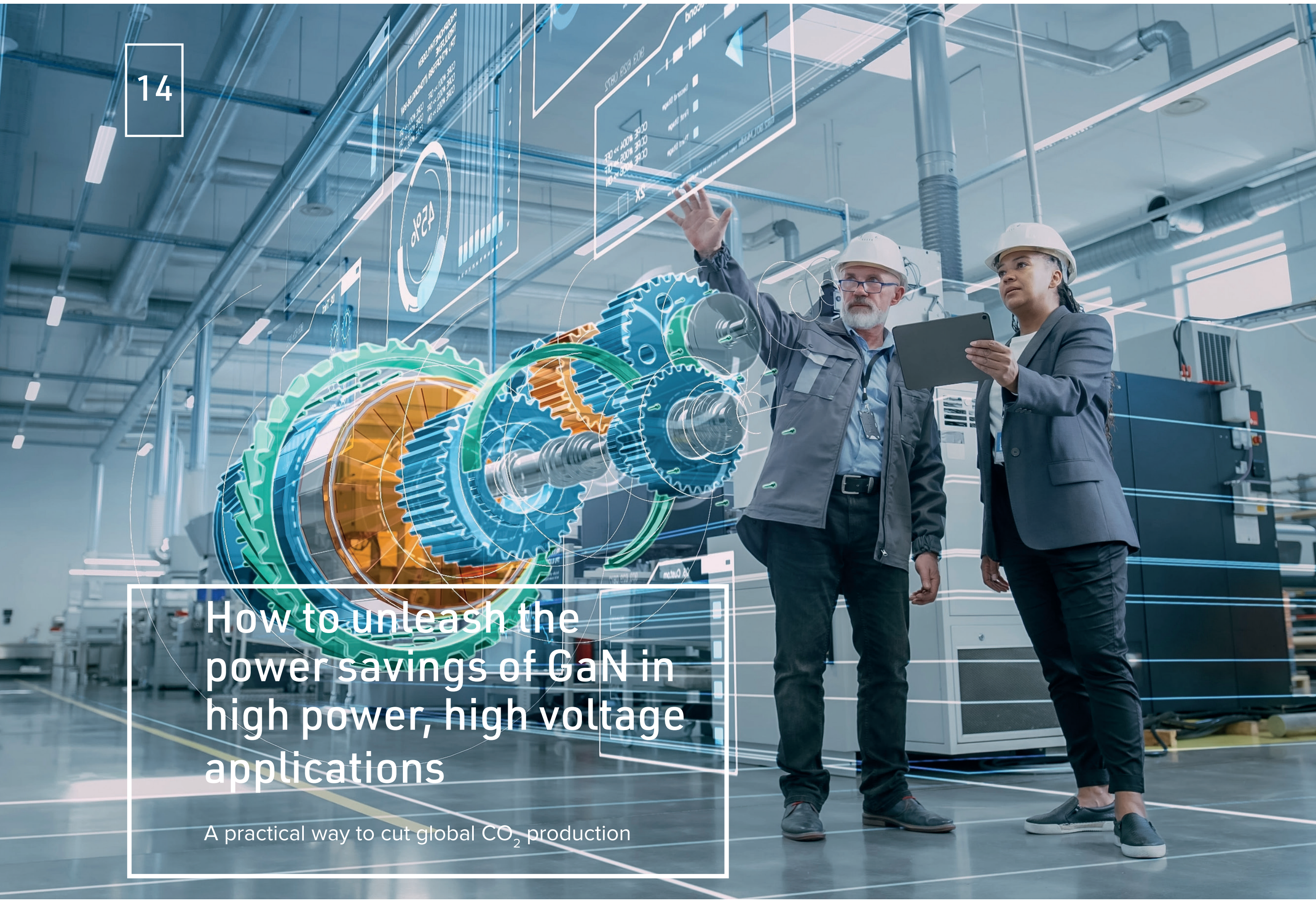
I'M DELIGHTED to welcome you to what can only be described as this 'bumper' issue of PEW. Not surprisingly, there's plenty of content focusing on wide band gap semiconductor materials, as the potential they offer in power electronics applications continues to drive much activity in the sector. As Fairfield Market Research predicts, the overall power electronics market will be worth almost $70 billion by 2030, largely driven by the growth in both SiC- and GaN-based solutions. In terms of the applications which are expected to benefit from these (as well as from 'traditional' silicon-based solutions), they are headed by the electric vehicle market, alongside AI and IoT, as well as industrial automation.

And a quick glance through our news pages confirms that the EV market seems to be particularly active at the current time. Indeed, if these news stories were the only point of reference an individual had when it came to EVs, one would imagine it is very much 'full steam (or battery) ahead' for this market. However, out in the commercial, real world, there seems to be far less certainty when it comes to the apparent heir to the internal combustion engine. One powerful example – Tesla EV sales were lower in the first quarter of 2024 than in the same period a year earlier. One quarter certainly doesn't indicate a crisis, for sure. However, combined with the apparent ambivalence of many governments across the globe to embrace EVs wholeheartedly, the EV market may not grow as quickly as required if it is to play its full part in the global 2050 net zero target.

Of course, much of the work reported on in these pages, alongside plenty of other EV-focused R&D, will be crucial in overcoming most, if not all, of the barriers which remain to the electric vehicle market gaining the necessary momentum. But only if the transition from fossil fuels to electricity is embraced wholeheartedly and managed quickly and efficiently by governments across the globe will the EV market engage top gear. For now, whether one believes that the fossil fuel lobby remains too powerful, or that governments are reluctant to 'inflict' the relatively high costs of EVs on their citizens, such positive actions are not matching the achievements of the power electronics sector's own ambitions.

And it is this uncertainty that threatens to impact the EV market for the near future at least. Yes, the cost of the vehicles is a major issue. Equally importantly, if I have purchased an EV, I want to be sure that any travelling I do is not inconvenienced by the need to find charging stations on my journey. And yet, the wholescale building of charging infrastructure won't happen until there are enough EVs on the road to make it worthwhile – and there will only be enough such vehicles when people are convinced there are enough charging stations...

Which brings us back to the understanding that governments across the world have within their, pretty much, sole power the future of the EV industry. Time to panic?!



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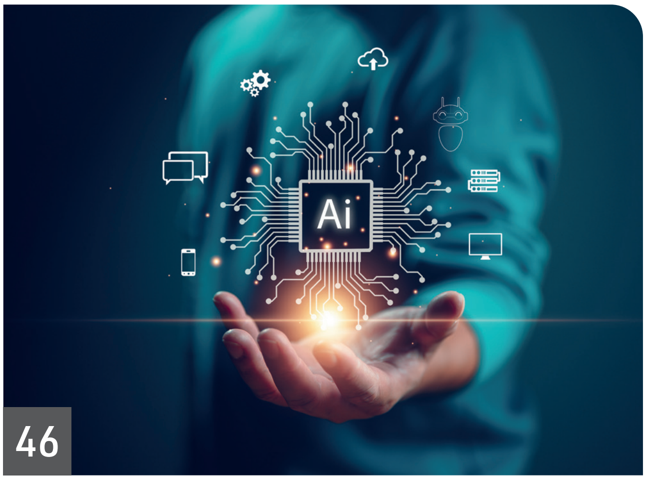

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Editor
Phil Alsop
phil.alsop@angelbc.com
+44(0)7786084559

News Editor
Christine Evans-Pughe
christine.evans-pughe@angelbc.com

Contributing Technical Editor
Richard Stevenson
richard.stevenson@angelbc.com
+44 (0)1923 690215

Sales & Marketing Manager
Shehzad Munshi
shehzad.munshi@angelbc.com
+44 (0)1923 690215

Design & Production Manager
Mitch Gaynor
mitch.gaynor@angelbc.com
+44 (0)1923 690214

Senior Event and Media Executive for Power Electronics International
James Cheriton
james.cheriton@angelbc.com
+44 (0)2476 718970

Publisher
Jackie Cannon
jackie.cannon@angelbc.com
+44 (0)1923 690205

CEO Sukhi Bhadal
sukhi.bhadal@angelbc.com
+44 (0)2476 718970

CTO Scott Adams
scott.adams@angelbc.com
+44 (0)2476 718970

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Published by Angel Business Communications Ltd
6 Bow Court, Fletchworth Gate, Burnsall Road, Coventry CV5 6SP, UK.
T: +44 (0)2476 718 970
E: info@angelbc.com W: angelbc.com

Infineon SiC modules to power Xiaomi EV

SiC power modules and bare die products will be used in new SU7 until 2027

INFINEON will provide SiC power modules HybridPACK Drive G2 CoolSiC and bare die products to Xiaomi EV for its recently announced SU7 until 2027.

Infineon will provide two HybridPACK Drive G2 CoolSiC 1200 V modules for the Xiaomi SU7 Max. In addition, Infineon is also supplying Xiaomi EV with a broad range of other products per car, including EiceDRIVER gate drivers and more than ten microcontrollers in various applications.

The two companies have also agreed to further cooperate on SiC automotive applications using Infineon's SiC portfolio.

Zhenyu Huang, VP of Xiaomi EV and general manager of the supply chain department, said: "Infineon is an important partner with leading technologies and resilient manufacturing capabilities in power semiconductors as well as a highly scalable microcontroller product portfolio. The cooperation between the two companies will not only help stabilise the supply of SiC for Xiaomi EV, but also help us build a high-performance, safe and reliable luxury car with leading-edge features for our customers."

Peter Schiefer, president of Infineon's automotive division, said: "We are very pleased to work with dynamic players such as Xiaomi EV and provide them with SiC products designed to enhance the performance of electric cars even further. As the leading partner to the automotive industry, we are well positioned with our broad product portfolio, system understanding and multi-site manufacturing base to shape the mobility of the future."

According to the latest data from TechInsights, Infineon is the largest semiconductor supplier to the automotive industry. In addition to its number one position in automotive power semiconductors, Infineon also took the lead in the field of automotive microcontrollers last year.

US SiC R&D facility celebrates topping out

THE UNIVERSITY OF ARKANSAS has celebrated a milestone with the topping-out of the Multi-User SiC Research and Fabrication Facility.

The new semiconductor facility will enable the federal government – via national laboratories – businesses of all sizes and other universities to prototype with SiC, a capability that does not presently exist elsewhere in the United States.

Work at the facility is intended to bridge the gap between traditional university research and the needs of private industry. The aim is to accelerate technological advancement by providing a single location where chips can go from developmental research to prototyping, testing and fabrication.

The 21,760-square-foot facility, located next to the National Center for Reliable Electrical Power Transmission at the Arkansas Research and Technology Park, will feature approximately 8,000 square feet of clean rooms for fabrication and testing.

Education and training within the facility will also accelerate workforce development, helping supply the next generation of engineers and technicians in semiconductor manufacturing.

Pictured above: From left, Kim Needy, dean of the College of Engineering, signs a beam while Margaret Sova McCabe, vice chancellor for research and innovation, and Chancellor Charles Robinson observe.

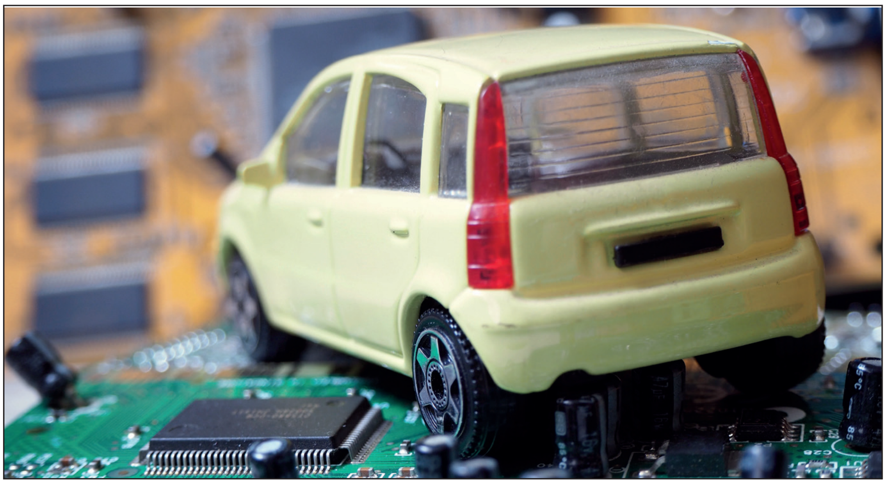
UK Government to invest £14M in power semi packaging

Slicing substrates with a 532 nm laser promises to trim the cost of producing GaN power MOSFETs without compromising performance

The UK Government has announced £16.6 million investment to give semiconductor researchers and businesses access to new equipment to help them test and make semiconductor chips for use in applications like electric cars and manufacturing equipment.

£14 million of the funding is targeted at power semiconductors.

The new tools, based predominantly in Newcastle and Strathclyde, is designed to help researchers and businesses of all sizes test applications in power electronics and improve their semiconductor packaging processes.



The investment, made through Innovate UK, comes as part of the UK's Semiconductor Strategy, which identified new ways of packaging and testing chips as a key area to drive performance improvements in semiconductors. Technology Minister Saqib Bhatti said: "New innovations in the way we package up semiconductors have the potential to transform whole industries and vastly improve consumer devices, all while driving long-term economic growth.

"This investment in open-access technology will make sure British researchers have the tools they need to rapidly turn semiconductor science into business reality, all while making hugely energy intensive sectors more sustainable.

"The open-access tools will cover a range of processes involved with designing and testing these semiconductors, including slicing silicon wafers into smaller chips and bonding complex materials together to make chips.Funding will also be used to help manufacturers improve the technology used to automate assembly processes, as well as helping build and test 'drives' which are pivotal in the conversion of energy into motion in electric vehicles, manufacturing equipment and more.

Mike Biddle, executive director, Net Zero at Innovate UK, said: "Innovate UK's investment into supply chains for Power Electronics, Machines and Drives shows the importance of these technologies to the UK economy and the global race to net zero.

"It is exciting to see the breadth of activity in semiconductor packaging as well as electric machine validation and manufacturing. The majority of this investment is strategically aligned with the National Semiconductor Strategy and helps grow the high-value post-wafer capabilities within the UK.

{The funding will build on an existing network of machinery open to researchers and businesses across the UK through Driving the Electric Revolution Industrial Centres (DER-IC), originally backed by £33 million of funding in 2019.

"DER-IC has previously partnered with the likes of McLaren Applied to test and develop new ways of manufacturing an 'electric drive train', a power electronics technology that will be used by companies producing automotives and aeroplanes to bring innovative and more efficient electric products to the market faster."

Matt Boyle OBE, executive chair of DER-IC, said: "This funding will allow us to help industry invest further in the technologies of Power Electronics, Machines and Drives (PEMD) manufacture.

"Industry has already invested heavily in these electrification manufacturing technologies since the start of the challenge. This additional equipment is being deployed to areas, capability and sectors where industry has stated that it will grow the UK supply chains for PEMD.

Paul Jarvie, centre lead for the DER-IC for the South West and Wales and Business Development Manager at CSA Catapult said: "This new funding will help us further improve our offering to the PEMD industry and develop innovative new technologies to drive us towards Net Zero.

Fraunhofer inverter project boosts EV performance

Dauerpower project with Porsche and Bosch uses SiC and novel packaging to achieves up to 30 percent performance increase

FRAUNHOFER IZM is working with project partners Porsche and Bosch, in a project called Dauerpower, to develop an electric inverter that can work at a lower operating temperature thanks to optimised cooling management, resulting in a lower power loss.

The compact three-phase drive inverter has a high continuous output of 720 kW or 979 horsepower and a rated current of 900 A

Eugen Erhardt, head of the project at Fraunhofer IZM, assesses the performance of the new system: "Compared to existing silicon-based inverters, our approach achieves an increase in performance of between 20 percent and 30 percent." The researchers achieved this increase in power density through the thermal optimisation of advanced materials and optimised embedding processes in production. Erhardt's group had already dealt with these in the SIC efficient predecessor project.

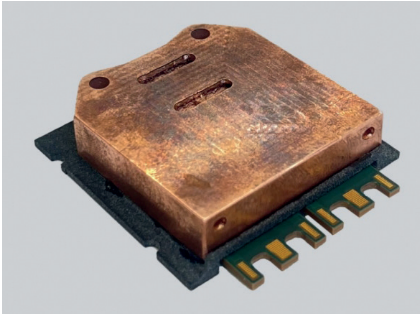
To prevent the passive components of an inverter, such as capacitors and copper elements, from being damaged by heat build-up, conventional systems throttle their maximum output in continuous operation.

The system developed by Fraunhofer IZM avoids this by using SiC transistors. Two of these SiC transistors are applied directly to a ceramic substrate at Fraunhofer IZM using an innovative prepackaging process. These prepackages can then be flexibly embedded in conventional PCBs. Thanks to the thin design and a reduction in the materials required, less mechanical stress and more uniform deformation behaviour occurs in case of heat exposure. In addition, the segmented ceramic substrates make optimum use of the limited space available to best meet the specific requirements of the automotive industry.

In addition to the optimised materials, the researchers also looked at how to cool the individual components more efficiently. The better the cooling effect, the less expensive semiconductor material is required, as the chips can be arranged even more compactly.

The researchers' aim is to achieve a high level of thermal integration of the various semiconductor elements, as well as passive components such as capacitors and copper conductors. For this purpose, the temperature-critical components are connected directly to the cooling system via silver sintered connections and thermally integrated in the best possible way: Thanks to a parallel arrangement, the cooling liquid reaches all heat sinks and connected semiconductor elements simultaneously, and the thermal energy is dissipated evenly.

Copper is also being used for the first time in a 3D printing process to manufacture the cooling elements, allowing the excellent thermal conductivity of copper to be combined with the full flexibility of 3D printing, instead of only being able to access aluminium heat sinks as before.



Compared to CNC milling processes, 3D printing allows a great deal of freedom with regard to the design of the cooling channel and, in turn, optimum utilisation of the limited installation space.

In addition to advances in materials and production processes, the scientists were also able to achieve greater modularity of the individual elements for the prototype. While the concept envisaged in the previous project was still based on a solution in which all components were permanently connected to each other, the elements of the inverter can now be replaced and repaired more easily as sub-modules.

Following a simulation phase, the prototype is currently under construction and will ultimately undergo an extensive testing process at Porsche AG in order to one day find its way into series production.

The Dauerpower project was launched in 2021 and received funding of €1.2 million from the German Federal Ministry of Economics under the reference number 19I21023C.

In addition to advances in materials and production processes, the scientists were also able to achieve greater modularity of the individual elements for the prototype. While the concept envisaged in the previous project was still based on a solution in which all components were permanently connected to each other, the elements of the inverter can now be replaced and repaired more easily as sub-modules

What's next for SiC?

The focus is shifting, says Yole

SiC IN POWER ELECTRONICS is on track to reach $10B in revenue by the end of this decade, and the strong growth in 2023 was a crucial step in multiple applications, writes market research firm Yole Group in a Viewpoint article.

BEV remains the key market driver, with Tesla's 1.8 million cars shipped in 2023 while major OEMs such Hyundai, BYD, Xpeng, Nio and many others are increasingly launching 800V BEVs.

All the major SiC device players are supplying this application, helping it achieve record revenue in 2023.

In the meantime, other applications, such as EV chargers, power supplies, photovoltaic, etc., are waiting for sufficient volume at a competitive cost for the next generation SiC device designs.

It was the same in SiC wafer and epiwafer businesses, with record 2023 revenues.

However, Yole says there is a concern that shipments are slowing down due to the weakness of the global economy. Many players are re-evaluating the timing of the return to growth; could it be in Q3 of 2024 or later?

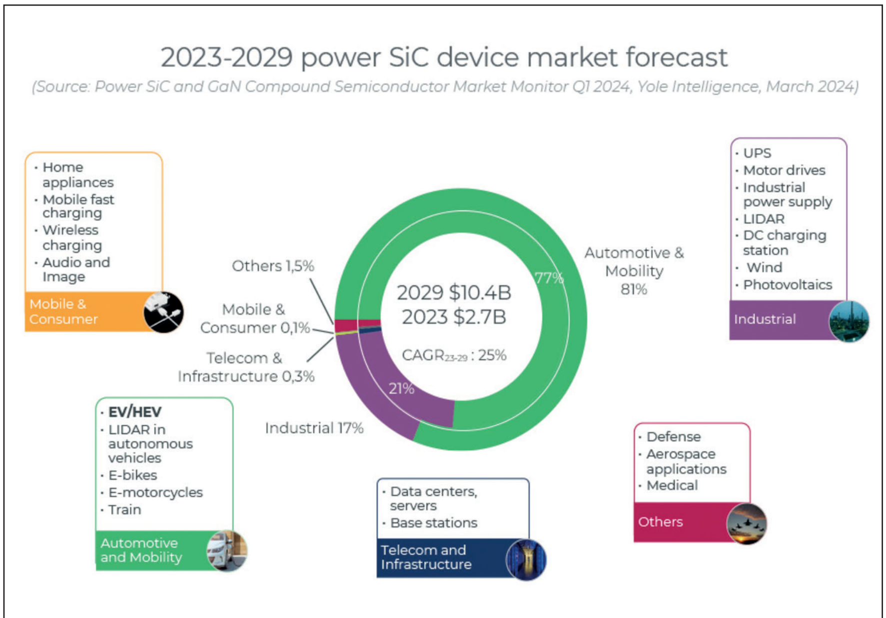
The SiC supply chain is closely monitoring it, as 2024 results will be highly impacted.

In the meantime, the supply chain is reshaping. This is seen in the ranking of players by revenue in 2023: Currently, Yole sees at least two Chinese companies ranked in the top five in SiC wafer and epiwafer.

This also indicates the maturity of equipment supply supporting this rapidly growing SiC market.

Another critical consideration is the demand-supply issue. In the past years, SiC wafer was in tight supply; an LTA with a wafer supplier is essential to secure access to SiC wafers.

However, following significant capacity expansion in the past two years, the discussion is moving to price and the risk of overcapacity, says Yole.



UK PEMD pilot manufacturing centre opens

Driving the Electric Revolution Industrialisation Centre (DER-IC) South West and Wales opened its doors

DER-IC South West and Wales hosted the Secretary of State for Wales, David TC Davies, for the official opening of its advanced packaging facility at the Compound Semiconductor Applications (CSA) Catapult's Innovation Centre in Newport.

DER-IC South West and Wales is part of the wider DER-IC network, which has four centres across the UK and offers open access equipment, facilities, and expertise to the Power Electronics, Machines and Drives (PEMD) manufacturing supply chain. PEMD are underpinning technologies that support electrification and will, in turn, enable Net Zero and boost the UK economy.

The official opening included a tour of the new facilities and keynote speeches from Jayakrishnan Chandrappan, Head of Advanced Packaging at CSA Catapult and Paul Jarvie, DER-IC South West and Wales Centre Lead. The speakers highlighted the capabilities of the new equipment and the specialist expertise that is available at CSA Catapult.

The new DER-IC South West and Wales facility can be used by manufacturers as a prototype facility for developing semiconductor and compound semiconductor packages using multi-material 3D printing, such as ceramic and metals.

These new facilities will support the UK government to deliver its National Semiconductor Strategy, a policy paper outlining how the UK will realise its ambitions to become a science and technology superpower. The strategy builds on the UK's foundations and strengths in semiconductor technology.

Welsh Secretary David TC Davies said: "It was a fascinating visit to the DER-IC and see this brilliant resource for UK PEMD manufacturers. The UK Government is proud to support the compound semiconductor cluster in south Wales, which is vital to our ambition for the UK to lead the world in science and technology. The processes being developed here means that the supply chain within the UK is strengthened, helping to protect the industry and fostering job creation."

The equipment showcased at the launch event included the centre's advanced 3D printing equipment suite. The equipment is the UK's first in an open-access setting and stands as a pioneering facility. The equipment enables the integration of combination, mixed metal, and ceramic printing technologies for chip packages, heat sinks, and printed circuit board (PCB) designs.

The centre has already attracted significant interest from major industrial partners across the aerospace and transport sectors.

Dycotec Materials is looking to develop a 3D printing process to improve performance, reliability and significantly reduce the cost of packages and modules for automotive applications.

Meanwhile, CSA Catapult and Carbon Forest Products are involved in a project to create a 3D graphite heat sink - a key component used to move heat away from an electronic device - for use in automotive systems.

DER-IC South West and Wales Centre Lead Paul Jarvie commented: "The opportunities this centre presents to the PEMD manufacturing supply chain are significant. We're inviting anyone in the PEMD supply chain who is interested in innovation and technology development, manufacturing scale-up and commercialisation, as well as skills and workforce development to engage with us.

"The new DER-IC facility, installed using the funding from the DER Challenge, allows industry to explore what materials it can use to create packaging that allows chips to reach their full potential within electric cars, trains, boats and other modes of transport. Our facilities can support manufacturers to de-risk innovation and attract investment in this area. We can help develop lighter, more energy-efficient components, which can handle more power, are less expensive, and can offer better overall thermal performance."

Mike Biddle, executive Ddrector for Net Zero, Innovate UK said: "As key funders of both the CSA Catapult and DER-IC, Innovate UK is delighted to see the opening of the DER Lab in South Wales, a first in the UK. It shows the impact that different areas of the Innovate UK system coming together can have. It's another example of how we are investing in cutting edge capability in Wales to meet the needs of businesses across the UK, and against the commitments we have made in our collaborative innovation plan for Wales. The Lab is a cutting-edge resource for industry to de-risk innovation and strengthen the supply-chain – this will be an invaluable facility for the semiconductor sector and the diverse PEMD community."

Although this is the official centre launch, the doors to the facilities at DER-IC South West and Wales are already open and being used by PEMD manufacturers from across the UK.

BAE Systems and Eaton expand EV truck collaboration

New solutions increase EV system offerings to support medium- and heavy-duty commercial vehicles

BAE SYSTEMS and Eaton, a power management company, are expanding their collaboration to include EV solutions for heavy-duty trucks.

In 2023, the two companies signed a memorandum of understanding to provide electric drive technology solutions for the medium-duty truck market.

The expanded collaboration now includes heavy-duty applications, offering manufacturers a complete line of electric drive systems for commercial trucks above 19 tons. BAE Systems will now combine its electric motor and power electronics with Eaton's HD 4-speed EV transmission to provide a full heavy-duty EV system.

Along with the existing MD-4 solution, the integrated systems are designed for medium- and heavy-duty applications, including pick-up and delivery trucks, school and transit buses, and material handling, refuse, and regional haul trucks.

"We are combining our expertise and proven technology to provide customers with a complete EV solution," said Bob Lamanna, vice president and general manager of Power & Propulsion Solutions at BAE Systems.

"By expanding our scope to include more vehicle ratings, our robust system ensures high performance and reliability across a wider range of classes and sizes," said Mark Kramer, business unit director, ePowertrain, Eaton's Vehicle Group. BAE Systems says its power electronics feature advanced materials and a compact, modular design that uses fewer parts, making it highly reliable and adaptable to diverse platforms.

Its electric propulsion technology is developed, manufactured, and serviced at its facilities in Endicott, New York, Rochester, UK, and Guaymas, Mexico.

SiCrystal and ST expand SiC wafer agreement

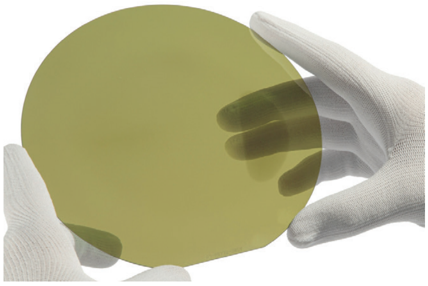
Multi-year agreement governs supply of larger volumes of SiC substrate wafers manufactured in Nuremberg

Rohm and STMicroelectronics have expanded its existing multi-year, long-term 150mm SiC substrate wafers supply agreement with SiCrystal, a Rohm group company.

The new agreement governs the supply of larger volumes of SiC substrate wafers manufactured in Nuremberg, Germany, for a minimum expected value of $230 million.

Geoff West, EVP and chief procurement officer, STMicroelectronics, commented: “This expanded agreement with SiCrystal will bring additional volumes of 150mm SiC substrate wafers to support our devices manufacturing capacity ramp-up for automotive and industrial customers worldwide. It helps strengthen our supply chain resilience for future growth, with a balanced mix of in-house and commercial supply across regions.”

“SiCrystal is a group company of Rohm, a leading company of SiC, and has been manufacturing SiC substrate wafers for many years. We are very pleased to extend this supply agreement with our longstanding customer ST. We will continue to support our partner to



expand SiC business by ramping up 150mm SiC substrate wafer quantities continuously and by always providing reliable quality,” said Robert Eckstein, president and CEO of SiCrystal, a Rohm group company.

Power electronics market to reach $69.7B by 2030

UK-BASED Fairfield Market Research’s latest report estimates that the global power electronics market will reach $69.7B by 2030, surging at a CAGR of 7.3 percent from 2023 to 2030.

This growth is fuelled by the rising demand for electric vehicles (EVs) and renewable energy integration, along with the increasing focus on sustainable practices and technologies like Artificial Intelligence (AI) and Internet of Things (IoT).

Industrial automation, and the rise of smart factories are also creating a significant demand for power electronic devices for precise control and energy efficiency, according to Fairfield.

A senior analyst at Fairfield said: “Advancements in wide-bandgap semiconductors and the growing emphasis on sustainable solutions will further propel market growth.”

Key insights are that SiC is the dominant material category and is expected to maintain dominance due to its superior performance. GaN is witnessing the fastest growth due to its efficiency at high frequencies. Power modules are the fastest-growing device category due to their ease of integration and reliability.

Low voltage (below 1kV) systems will remain dominant due to their versatility and safety features, while medium voltage category is witnessing the fastest growth due to its application in renewable energy and electric vehicles.

The report is called: ‘Global Power Electronics Industry Analysis, Size, Share, Growth, Trends, and Forecast 2023-2030’

> Industrial automation, and the rise of smart factories are also creating a significant demand for power electronic devices for precise control and energy efficiency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WE-PD
7447773010 DATASHEET
Lead Time: 12 Weeks
Current Stock: 7500 pcs.
Future Stock: 8000 pcs in 4 weeks
12500 pcs in 12 weeks
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How to unleash the power savings of GaN in high power, high voltage applications

A practical way to cut global CO_2 production.

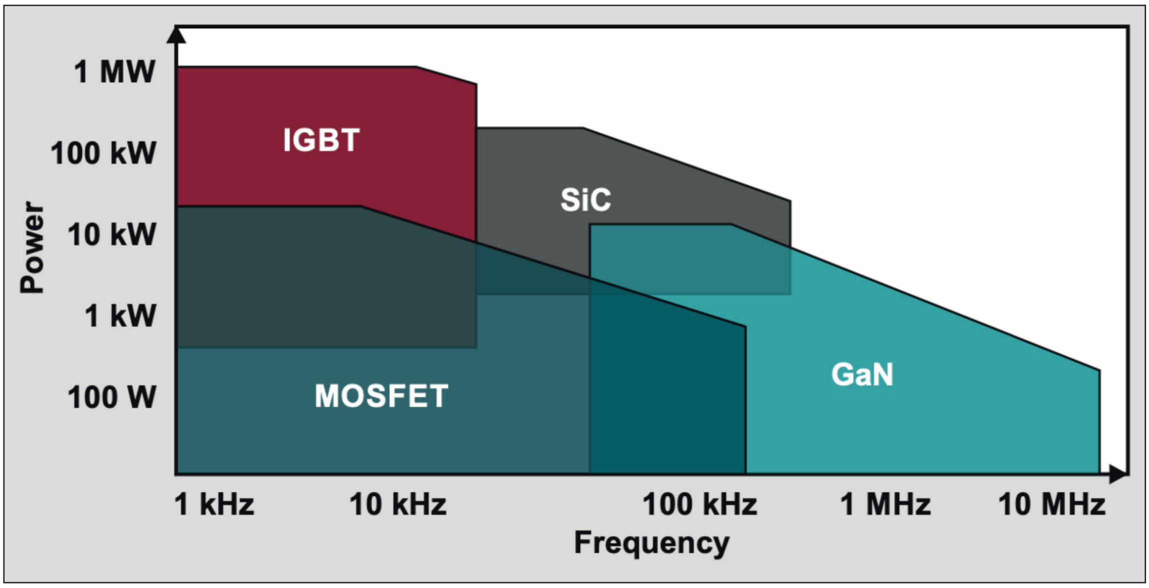
BY RUPERT BAINES, CEO, QPT LIMITED

EVERYONE wants to do something about climate change and we have a solution that could have a major impact on reducing CO_2 production. Sometimes, with our tongue firmly in our cheek, we say "saving the planet through better motor drives". Electric motors currently use 50% of global electricity, most of which is produced from burning fossil fuels. This will increase due to the inevitable move to electrification to hit net zero targets with rapidly increasing numbers of heat pumps and electric vehicles

Electric motors and systems are the largest, single-energy, end use and account for half of global electricity consumption according to a recent International Energy Agency report. This report expects that, without policy change by 2030, electromagnetic motor use will produce 8,570 Gigatonnes of CO_2 per year.

The elephant in the room is the fact that electric motors are often shockingly inefficient. Depending on the application, up to 25% of the electricity is wasted. Reducing this wastage means less CO_2 has to be produced. The International Energy Agency said "There is a huge, untapped potential for energy efficiency in electric motors. However, the energy efficiency of motors has been neglected in comparison with other sustainable energy opportunities."

77% of electric motors do not use motor control electronics (variously called controller, inverter or Variable Frequency Drive - VFD) to control them which is very inefficient. The remaining 23% have VFDs to adjust the motor speed which is less wasteful. However, these are still inefficient. This is because they use slow transistors as switches. The faster the transistors in the VFD switch, the less



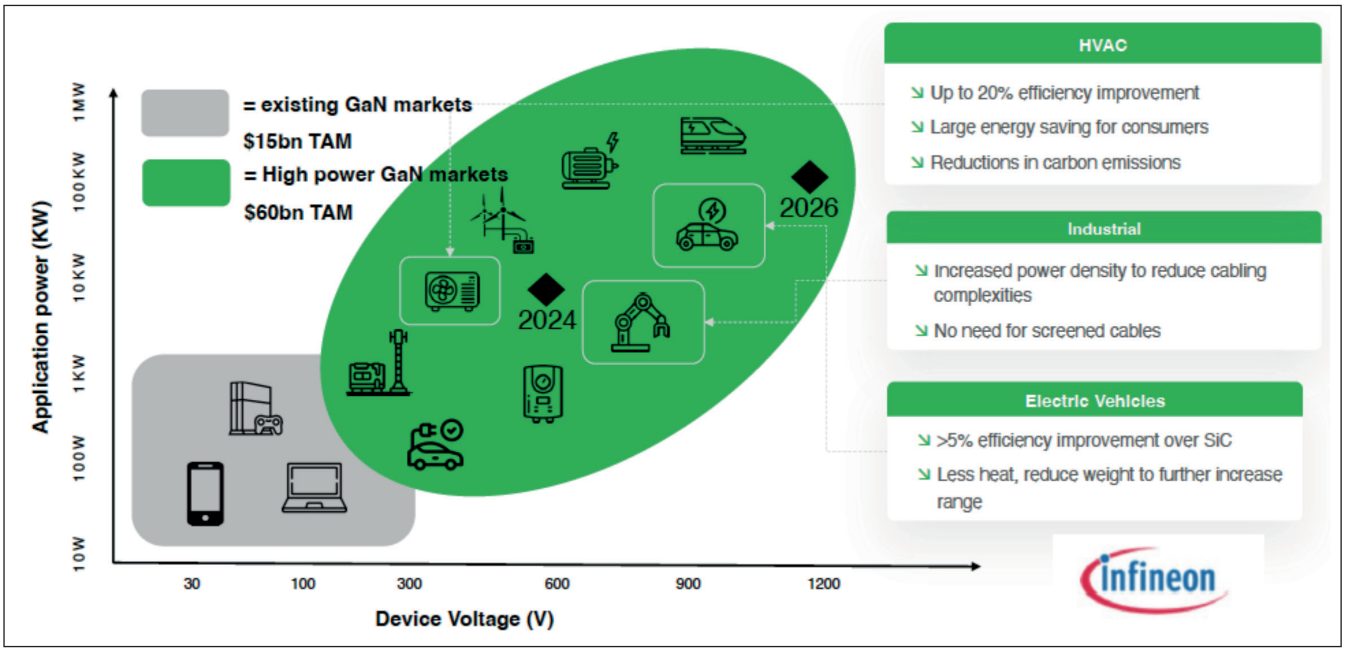
time is spent in the transition zone where energy is wasted: VFDs today often switch at only 4kHz. Traditionally silicon (Si) transistors have been used but they are reaching the limits that they can be switched at so faster Silicon Carbide (SiC) transistors are being used. For example, in the automotive world, SiC is now increasingly used in traction inverters. However, trying to drive either technology even faster, with frequencies higher than 100kHz to reduce wastage, creates problems with overheating and RF interference (RFI).

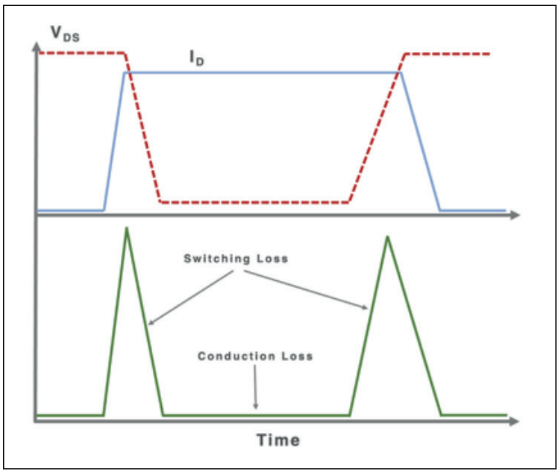
GaN is inherently a better semiconductor than Si or SiC. It has less capacitance, faster switching and no body diode. But it has been hard to use and has a reputation for being fragile.

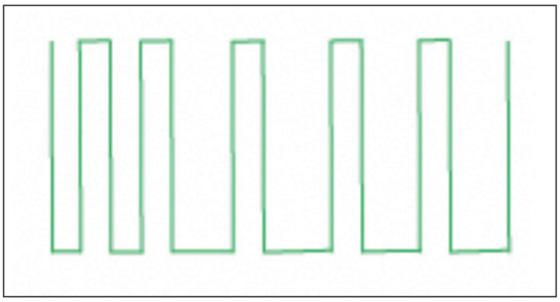
The graph shows that GaN has the ability to switch much faster than SiC - but it also shows how people must think GaN can only be used at low power (up to 10kW). This is what QPT solves with its qGaN technology.

At present, GaN has had to be confined to the low power applications and soft switching that uses less that 100kHz, such as chargers and computer power supply units with a TAM of $15bn. This new approach unleashes GaN to be driven at high speed to live up to its full potential and thus unlocking a huge new market of high-power, high-performance applications in HVAC, industrial application and electric vehicles with a TAM of $60bn.

The problem is that when you go above this 1 00 kHz point, you are in RF microwave territory. Power Electronics is currently about high power in the kWs with tens to hundreds of Amps but only low frequencies in the KHz. Microwave is typically low power in the mWs and high frequencies in the MHz. QPT's solution is to deploy microwave techniques

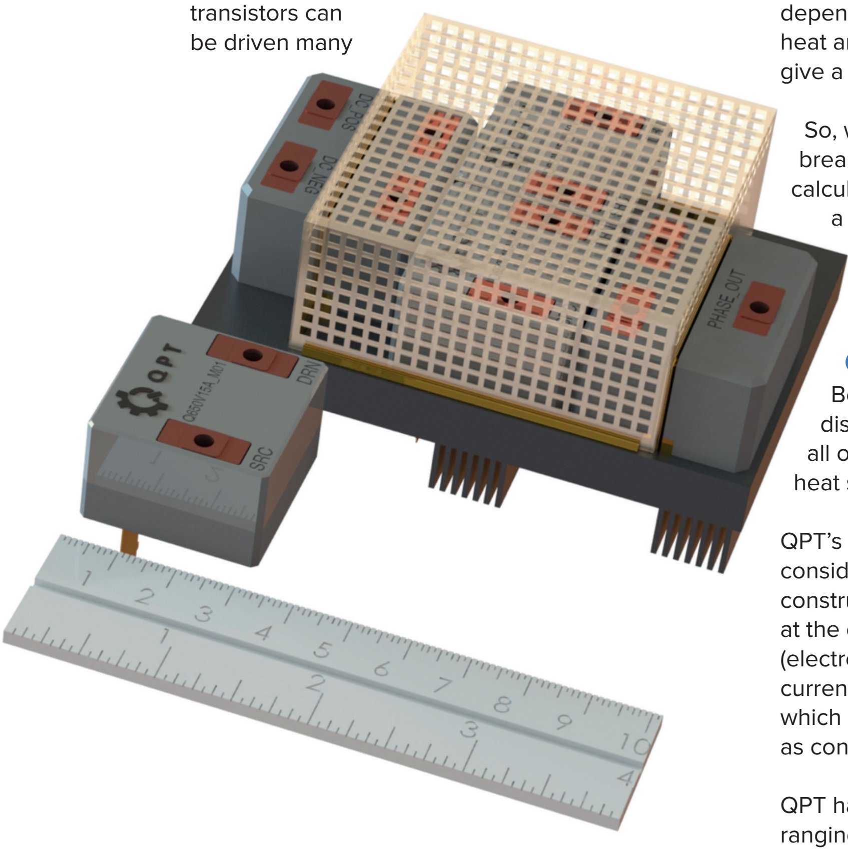






so that these two problems of overheating and RF interference are solved. Combining them together opens up a new future for Power Electronics kW and MHz, i.e., tens to hundreds of Amps at MHz speeds and dramatically higher efficiencies.

As a result, GaN transistors can be driven many times faster than any existing technology.



This has two implications. The first is dramatically less time in the transition region where energy is wasted. The diagram shows that the rise and fall times (Tr & Tf) where energy is wasted in the resistive region) are less than one nanosecond. The illustration on the left shows the sloping rise and fall where there switching losses whilst below these are near straight up and down so switching losses are dramatically reduced. Secondly, because the transistors are switching faster (< 1ns Tr/Tf), we can use a higher frequency Pulse Width Modulation (PWM) signal. Instead of 4kHz or 100KHz, the QPT system typically runs at 1MHz and could be even faster.

This enables a sinus filter to be integrated into the architecture because the frequency is high so smaller, cheaper filters can be used to reduce size, cost and weight.

Also, because the PWM frequency is so far from the motor drive frequency, the Low Pass Filter (LPF) action is very effective. Whereas most VFDs send a "dirty" PWM to the motor, the QPT output is almost pure sine, which very much better for the motor with less eddy currents (which cause heat & stress on the windings), less acoustic noise & vibration, essentially no dV/dt stress, no DC path, lower torque ripple, etc.

This means that a VFD can now be created that is up to 80% more efficient. In overall terms of total electricity usage by the VFD and motor together, this equates to a reduction of around 10% depending on the application. Plus, with less waste heat and stresses, the motor reliability improves to give a longer MTBF.

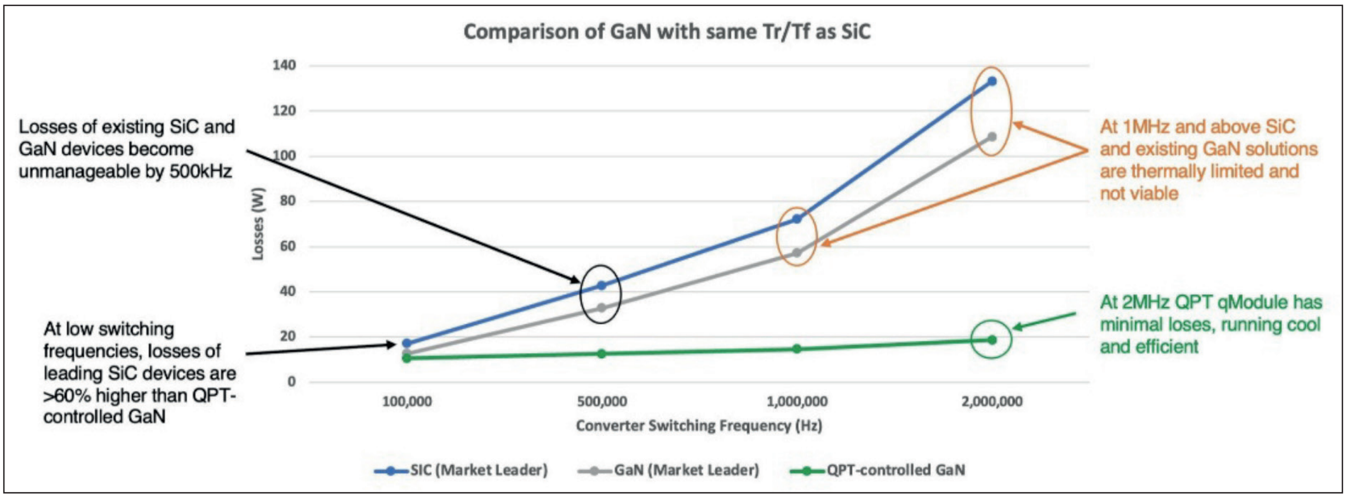
So, what could this disruptive technology breakthrough deliver when deployed? We calculate that the improved efficiency equates to a potential of $66bn in annual energy savings, a saving of 1000TWh and even more importantly 400m tonnes of CO_2 that does not have to be produced.

Our qGaN module

Because our solution combines two different disciplines, we have created a module that has all our qGaN technologies incorporated together heat sink and RF shielding.

QPT's qGaN modules are designed with RF considerations in mind. The packaging and construction of the module allow for switching at the order of MHz without issues with EMC (electromagnetic compatibility). This technology is currently capable of producing 7.5kW motor drives, which are vital in the industrial sector for things such as conveyor belts, mixers, and air conditioning.

QPT has a roadmap for high-power drives, ranging from 20 to 120kW, and anticipates these



to launch over the next year. Furthermore, with much less wasted energy, the module wastes less heat, eliminating the need for an active cooling system or heavy heatsink, or at least reducing the requirements of such systems. By adding copper around the die to conduct thermal energy away, there will be parasitic capacitance couplings, which degrade the switching characteristics of the transistor. QPT's passive cooling solution conducts heat away without the need for this.

Our VFD demonstrator

We have created a VFD that is a drop-in replacement for a common VFD to make it easy for manufacturers to include into their motor designs and even retro fit to existing ones so that they can take rapidly implement of its ultra-efficient and ultra-compact design. The elimination of RF interference means that costly, bulky cables to connect the VFD to the motor are eliminated. In fact, the VFD is now so small at a twentieth of the size of current equivalents that it can be mounted on the motor to create a compact, integrated solution.

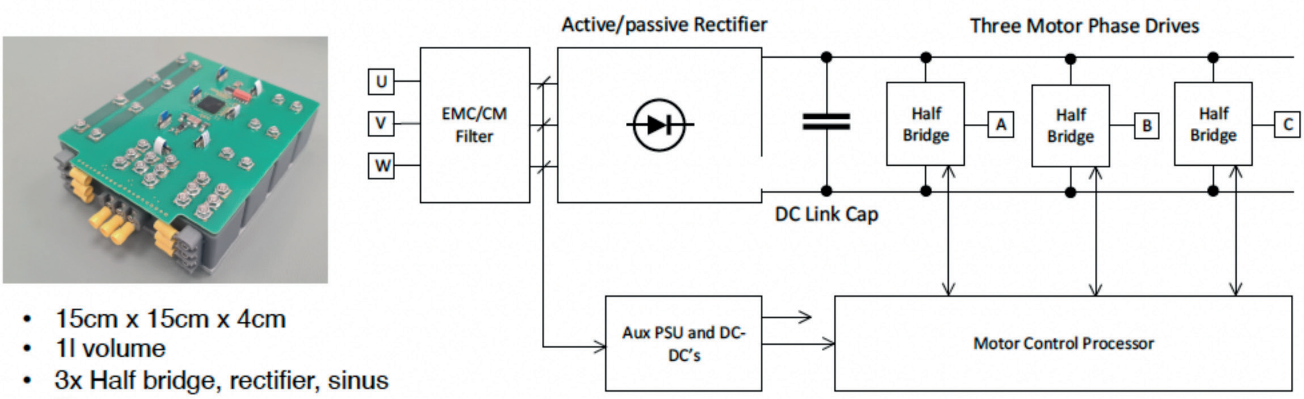
This is a 400V (230V 3 phase), 7.5kW qGaN VFD. It has a 1MHz internal switching PWM with less than 1 ns switching time and a compact integrated sinus filter. The output is from zero to 500Hz (0-300rpm) with pure wave (~0% THD). The active rectifier has less than 5% THD, no electrolytic capacitors and therefore a high MTBF.

Summary

The current thinking is that SiC is the next great thing for Power Electronics with huge investments to support it. But, while SiC has its place, GaN is fundamentally a better semiconductor and will displace Si and SiC in many applications with motors being one.

As we have shown, there is a barrier of overheating and RFI for SiC that is becoming increasingly apparent when trying to use it for more challenging applications and is being ignored in all the SiC hype. Our GaN technology enables GaN to greatly surpass SiC with much greater efficiencies and power handling capabilities so that it will be the true future of Power Electronics.

Saving the planet through GaN may seem be a hyperbole but net zero and the electrification of everything are critical for humanity and we need to be doing everything we can to get there.
Those of us in the PE community have the challenge to make this work: but it is a challenge we need to rise to for the sake of our planet and our children. Better technologies like GaN at these higher frequencies to reduce energy wastage can have a big part in making this happen.



- 15cm x 15cm x 4cm
- 1l volume
- 3x Half bridge, rectifier, sinus filter, control processor

SiC MOSFETs

Scrutinising the gate atom by atom

Atom probe tomography unveils the composition and the distribution of key elements in the vicinity of the interface SiO_2 and SiC

BY LAKSHMI KANTA BERA, SHIV. KUMAR, NAVAB SINGH, UMESH CHAND, ABDUL HANNAN BIN IBRAHIM ABDULLAH YEO, VOO QIN GUI ROTH AND SURASIT. CHUNG FROM A*STAR AND PIERRE-YVES CORRE FROM CAMECA INSTRUMENTS

OVER THE LAST DECADE, much effort has been devoted to the development of the SiC MOSFET. This is paying off, with sales soaring, driven by the uptake of this device in electric vehicles.

The success of the SiC MOSFET comes from its key attributes. One great strength is its wide bandgap, enabling high-temperature operation and a trimming of energy loss during device operation. Additional assets include its high thermal conductivity, aiding efficient heat dissipation and helping maintain device performance and longevity; and a simple integration flow, following in the footsteps of silicon technology, that involves the growth of SiO_2, using thermal oxidation.

However, the SiC MOSFET has an Achilles heel. In stark contrast to the interface of silicon and its native oxide, SiO_2, that grown on SiC is riddled with a high interface-state density. The numerous imperfections significantly reduce carrier mobility in the MOS channel and threaten device reliability.

Due to these significant concerns, much effort has been devoted to understanding the origins of the high density of interface states. This has been attributed to carbon-related defects, including C-clustered, C-interstitial, and C-vacancies. Within the scientific community, it is widely agreed that these defects play a significant role in influencing the density of interface states at the SiC/SiO_2 interface.

Many studies, such as those investigating native point defects and carbon clusters in 4H-SiC, as well as the structure and energetics of carbon-related defects in SiC, have provided much insight into the impact of these carbon-related defects on material properties. However, despite many years of investigation by several research groups, the distribution of different elements and compounds in bulk SiO_2 and at the SiO_2/SiC interface is yet to be completely understood. To a large extent, this comes down to a lack of information at the atomic scale. There is a need to know the identity and the precise location of different species.

Two common techniques for materials characterisation that fall short in this regard are X-ray photoelectron spectroscopy and Auger electron spectroscopy. Both these forms of spectroscopy are hampered by a poor lateral resolution in the micrometre-range, as well as a relatively poor detection limit – it is around

0.1 atomic percent – that leads to a low detection sensitivity, and hampers complex quantification of chemical analysis.

Another widely used technique within the compound semiconductor community, secondary ion mass spectrometry, excels in detecting trace elements down to parts-per-billion levels. However, its sub-micrometre lateral resolution limits atomic-scale analysis. In addition, quantification of results is challenging, due to the dependency on ionization energy for secondary ion yield.

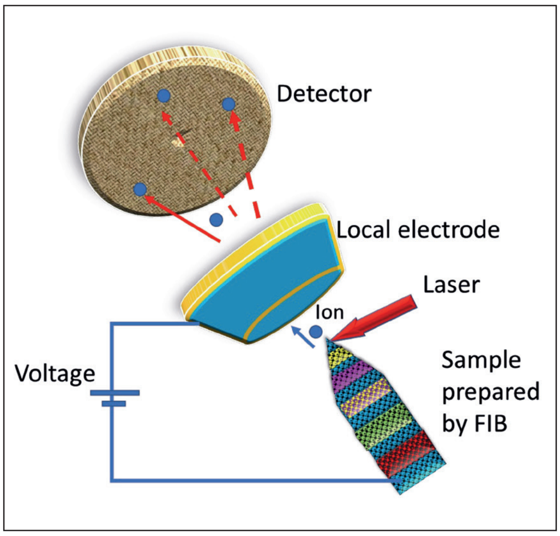
A versatile tool that provides detailed investigations at the sub-nanometre level is high-resolution transmission electron microscopy. Advances in one form of this, high-angle annular dark-field scanning transmission electron microscopy, have enabled, in special cases, three-dimensional characterisation at the atomic scale.

However, the ultimate characterisation technique for studying materials at the atomic level is atom probe tomography. This incredibly powerful technique, which our team from the Agency for Science, Technology and Research, Singapore, is using to scrutinise the interfaces of SiO_2 and SiC, can't be beaten when it comes to discovering the position of individual atoms in materials with nearly atomic resolution. One of its key merits is equal sensitivity for all elements.

Basic principles

Atom probe tomography operates on the principle of field evaporation, with surface atoms extracted from specimens with an electric field. This process involves directing a laser at the sample, alongside simultaneous high-voltage pulsing, conditions that cause surface atoms to evaporate with near 100 percent ionisation. The evaporated atoms are projected onto a position-sensitive detector for analysis.

To maximise the effectiveness of this technique, there is a need to prepare sharp needle-shaped specimens with a radius of 50-100 nm. Such samples ensure precise analysis through field evaporation of surface atoms. The chemical nature of the atoms is identified with time-of-flight mass spectrometry (see Figure 1 for an overview of this experimental setup).



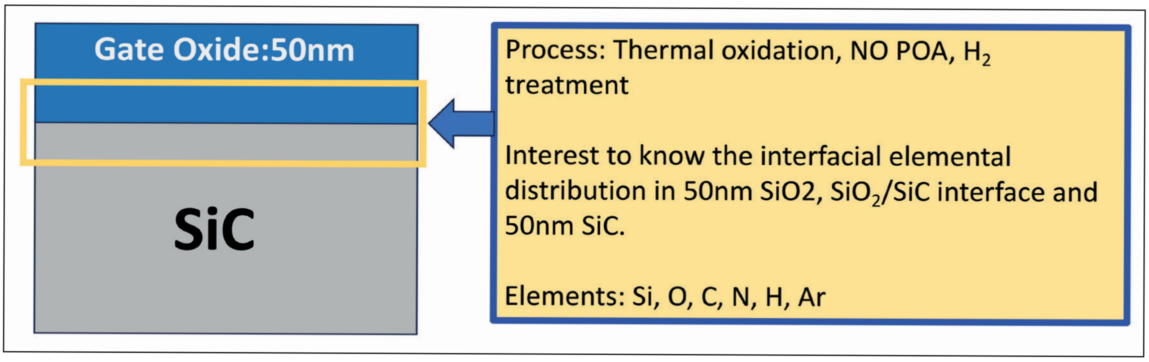
➤ Figure 1. The experimental setup for atom probe tomography.

After loading samples into an atom probe tomography analysis chamber, specimens are cooled to around 50 K and maintained in an ultra-high vacuum, typically 10^{-11} Torr. Applying a DC voltage of typically between 2 kV and 10 kV results in a high electric field at the surface of the tip. The field at the tip's apex is proportional to the applied voltage, and inversely proportional to its radius of curvature.

For electrically conductive materials, atom probe tomography involves the application of voltage pulses to the tip to generate an electrical field that induces field ionization. For less conductive samples a different approach is needed, with laser pulses ensuring the thermal evaporation of ions. The application of laser pulsing is especially advantageous in higher resistivity materials, such as semiconductors, where high-voltage pulses alone may be insufficient for promoting field ionisation.

The detection of ions that are liberated from the sample is correlated to the high-voltage and laser pulses. Ions are converted into a mass-to-charge-state ratio, measured in a unit known as the Dalton. This conversion is crucial for chemical identification of each ion, which is identified by the relationship between its time-of-flight and its mass-to-charge-state ratio.

A mass spectrum is produced during atom probe tomography – this is a histogram of the resulting



➤ Figure 2. Schematic cross section of sample for interest of investigation of several elements and their distributions.

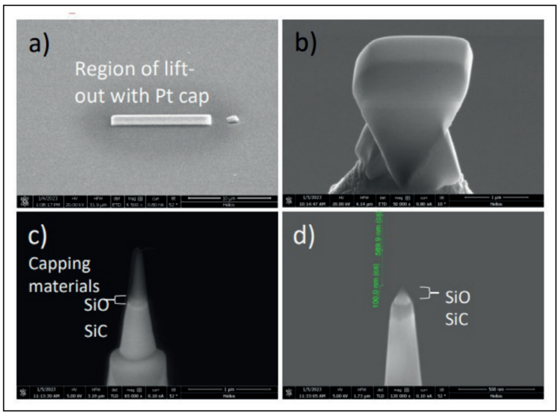


Figure 3. Typical scanning tunnelling electron micrscopy images of a sample ready for atom probe tomography measurements.

mass-to-charge ratio of the detected ions. The correlation of the chemical and physical properties of a specimen's surface aids characterisation of the mass spectra, as well as improving the precise accuracy of compositional material analysis and initial position at the specimen surface.

To determine the spatial distribution of atoms at the atomic scale, there is a need to generate a three-dimensional reconstruction of the analysed volume. This enables the determination of the local chemical composition of any arbitrary sub-volumes with a sub-nanometric resolution. Note that metals can provide concentration profiles with a depth resolution better than half an atomic plane.

Studying SiC MOSFETs

Within the SiC community, a two-step oxide-formation process has been widely adopted for making power MOSFETs. This involves either the thermal oxidation of SiC; or deposition of SiO_2, followed by interface nitridation with a nitric oxide gas. Neither process is ideal, leading to a high density of interface states. This issue continues to motivate effort to consider other processes for forming the gate oxide.

We have used atom probe tomography to study SiC MOSFETs produced with alternative processes that have much promise. Our study has considered both pre- and post-oxidation treatment with and without hydrogen gas, and the impact of a post-oxidation anneal using nitric oxide.
Our interest lies in understanding the elemental distribution of silicon, oxygen, carbon, nitrogen, hydrogen and argon in SiO_2, the SiO_2/SiC interface, and SiC beneath the SiO_2 layer (see Figure 2 for an illustration of the cross section of different zones of the sample). Through the use of atom probe tomography, we are able to gain insight into the composition and structure of these materials, and ultimately enhance our understanding of device characteristics, including interfacial properties, reliability of the gate oxide and MOSFETs channel mobility. In turn, these findings can enhance the development of new technologies and materials with improved performance and functionality.

The preparation of our sample began by sputtering 100 nm of nickel, followed by 300 nm of platinum, on the oxide surface to prevent subsequent damage. We then used annular ion beam milling at 30 kV to produce a needle geometry with a tip diameter of no more than 100 nm (see Figures 3(a-d) for typical images of the prepared sample).

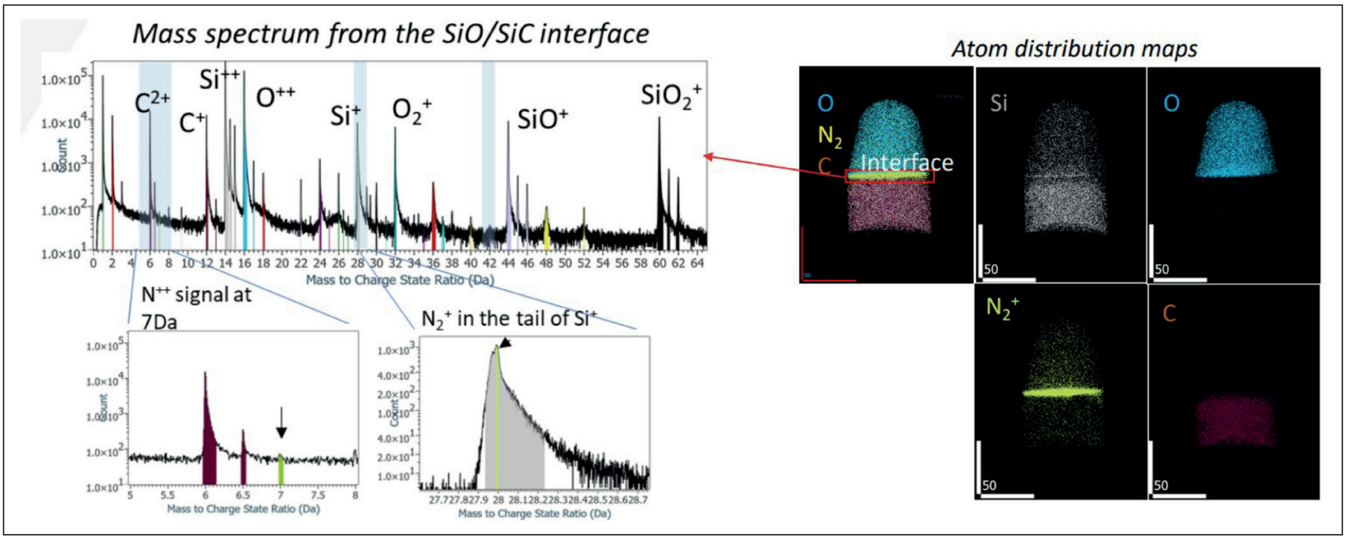
To mitigate damage from gallium implantation during the focused-ion beam process used for milling, all our specimens underwent low-energy cleaning with a 1 kV ion beam. This step is crucial for maintaining sample integrity and ensuring accurate results.

Our atom probe tomography measurements were undertaken with a laser power of 0.10 nJ/pulse to elucidate the influence of hydrogen gas treatment on the SiO_2/SiC interface. To ensure data reliability, we repeated experiments three times, for each type of sample. This ensured a rigorous approach, which gathered consistent, replicable results (see Table 1 for experimental details).

Atom probe tomography has enabled us to investigate the impact of hydrogen gas treatment before oxidation and after oxidation on the atomic distribution of different species in SiO_2 and at the SiO_2/SiC interface. Those species include carbon, nitrogen, oxygen, silicon and hydrogen (see Figure 4 for the line scan mass spectrum of different species and the three-dimensional elemental distributions for our sample that involved pre-oxidation hydrogen gas treatment, oxygen gas oxidation, and nitric oxide post-oxidation annealing).

Wafer	Experiments	Total Ions	Laser Power (nJ)	Pulse Frequency (Hz)	Temperature (K)
W4 (H_2 Anneal. +Oxi.+N_2 POA)	S1	13,952,096	0.10	367000	50
	S2	18,000,406	0.10	440000	50
	S3	30,000,210	0.10	200000	50
W6 (Oxi.+H_2 POA+ NO POA)	S1	13,952,096	0.10	367000	50
	S2	18,000,406	0.10	440000	50
	S3	30,000,210	0.10	200000	50

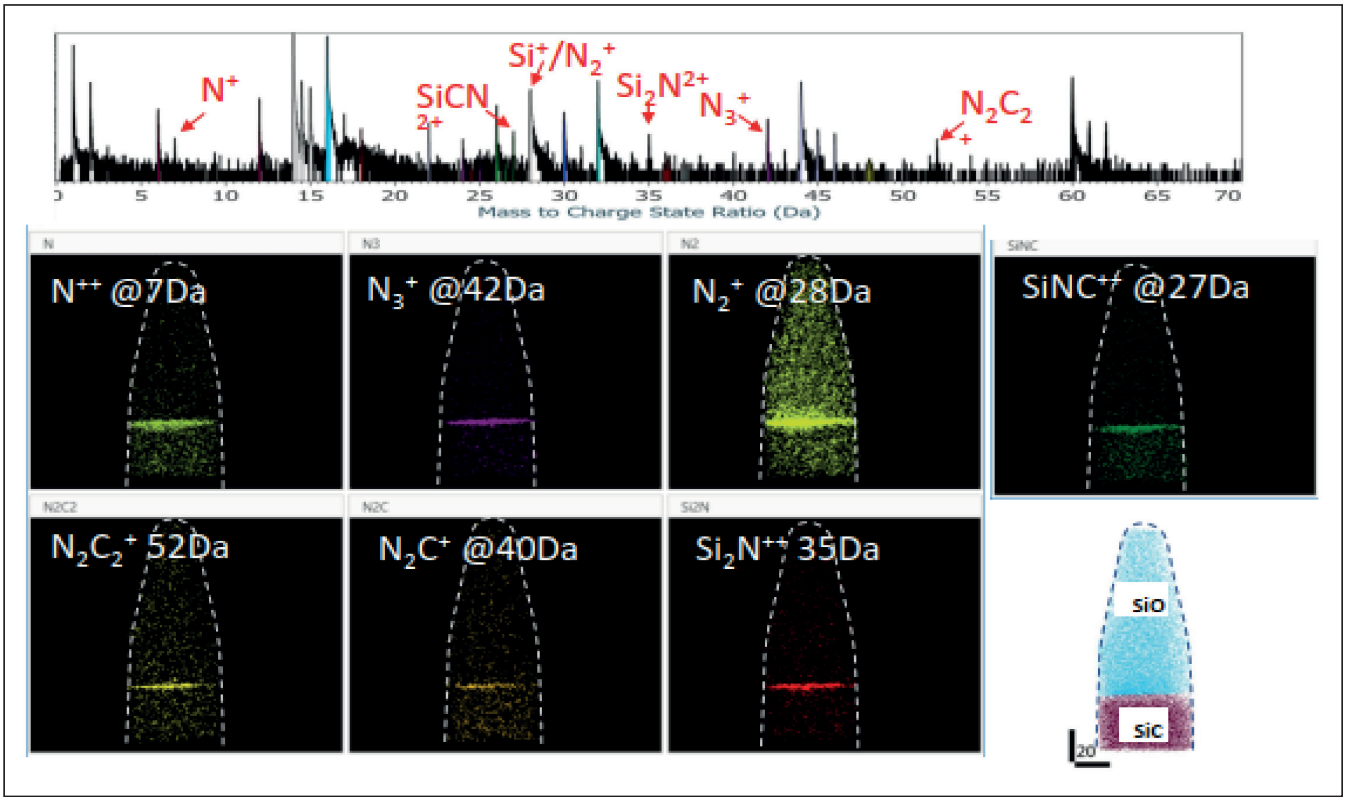
Table 1. Experimental parameters used for atom probe tomography analyses.



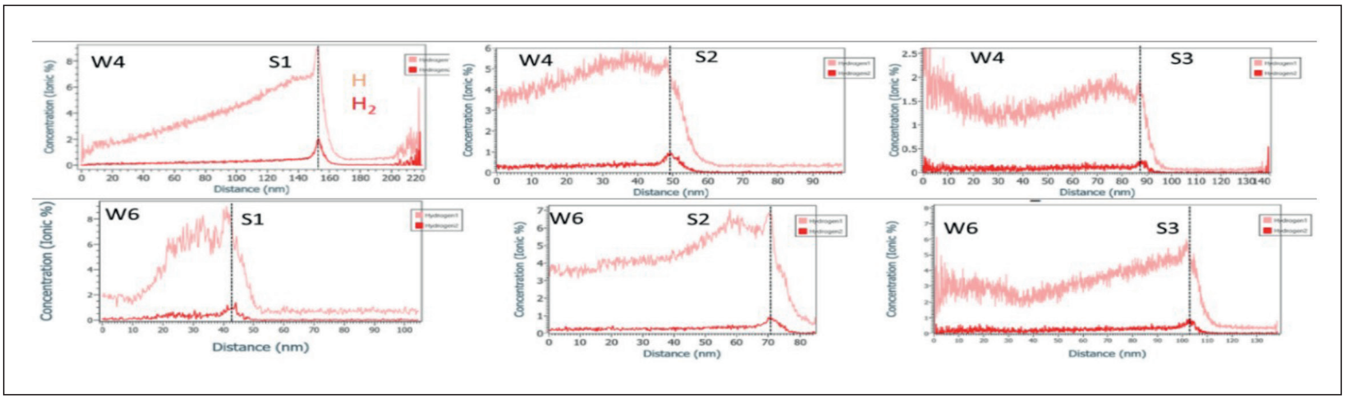
➤ Figure 4. The mass spectrum containing the interfacial region between SiO_2 and SiC from W4 obtained using atom probe tomography. Enrichment of nitrogen at the SiO_2/SiC interface is clearly observed in three-dimensional distribution maps.

The primary providers of the nitrogen signal are normally 7 Da (N^{++}), 14 Da (N^+), and 28 Da (N_2^+). Of these three, the detection of a possible N^+ signal at 14 Da is obstructed by the large Si^{++} signal.

For naturally abundant silicon, the ratio between Si-28/29 is 19.7. That's not the case for our sample with pre-oxidation hydrogen gas treatment, oxygen gas oxidation, and nitric oxide post-oxidation annealing. The presence of nitrogen at the interface changes this ratio, which is higher than that expected by a factor of 2.4. Using this piece of information, we applied a correction to deconvolute the nitrogen signal at the interface, obtaining an accurate concentration for this element of 4.0 percent. The three-dimensional atomic distribution clearly shows significant nitrogen



➤ Figure 5. Distribution of nitrogen-related signals in the analysed volumes obtained by atom probe tomography for the SiO_2/SiC interface subjected to oxidation with oxygen gas, and post oxidation annealing under hydrogen gas and then nitric oxide. Peak assignment has been undertaken based on the m/Z values: 7Da for N^{++}, 27Da for $SiCN^{2+}$, 28Da for Si^+ and N_2^+, 35Da for Si_2N^{2+}, 42Da for N^{3+}, and 52Da for $N_2C_2^{\ +}$, respectively.



➤ Figure 6. The plots show a reference for the observed trend of H and H_2 signals in the depth direction for the S1, S2 and S3 samples.

incorporation, predominantly at the SiO_2/SiC interface, with some traces in bulk SiO_2 as observed from the N^{2+} distribution map. Carbon is absent in both the SiO_2 and SiO_2/SiC interface.

We have also investigated the region-specific mass spectra of the SiO_2/SiC interface of the MOSFETs that undergo oxidation with oxygen gas, and post oxidation annealing under hydrogen gas and then nitric oxide. Region-specific mass spectra of the SiO_2/SiC interface are shown in Figure 5. There are a large number of nitrogen-containing peaks in this data, with red arrows used to indicate nitrogen-containing signals at the interface region.

The ejection of complex ions from this sample, a situation not observed in the other sample, suggests that the combination of post-oxidation annealing under hydrogen gas and then nitric oxide treatment at high temperatures may lead to the production of many compounds through a complex process. This process involves diffusion of hydrogen gas and nitric oxide, as well as a chemical reaction involving various atoms, including silicon, carbon, nitrogen, oxygen, and hydrogen.

On the other hand, the sample that has undergone hydrogen gas treatment before oxidation may have potentially taken part in hydrogen-termination, diffusion into interstitial spaces, and the creation of carbon-hydrogen bonds. Subsequent oxidation of the SiC surface layer may have decreased the possibility of a chemical reaction that forms many complicated compounds during post-oxidation annealing by nitric oxide.

We are surprised to note that our atomic concentration profiles show that there is nitrogen enrichment, confined at the interface to a depth of around 2.8 nm. We also note that we find no evidence for excess carbon or clustering in the bulk oxide, at the interface, or in SiC beneath the interface. Examining the hydrogen gas species, we observe an increase in the hydrogen signal in SiO_2 with depth, spikes at the SiO_2/SiC interface, and then a sharp decrease after crossing the interface.

The 2.8 nm-thick interfacial layer, rich in nitrogen and hydrogen, acts as a transition layer between materials. The presence of nitrogen and hydrogen plays a crucial role in reducing carbon cluster formation and passivating carbon or silicon-related defects at the interface. This passivation process helps to trim the interface state density and thus enhance the performance of the MOSFET, including its reliability. Further investigation is essential to verify both channel mobility enhancement and reliability properties of SiC power MOSFETs.

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GaN blossoms into full technology solution

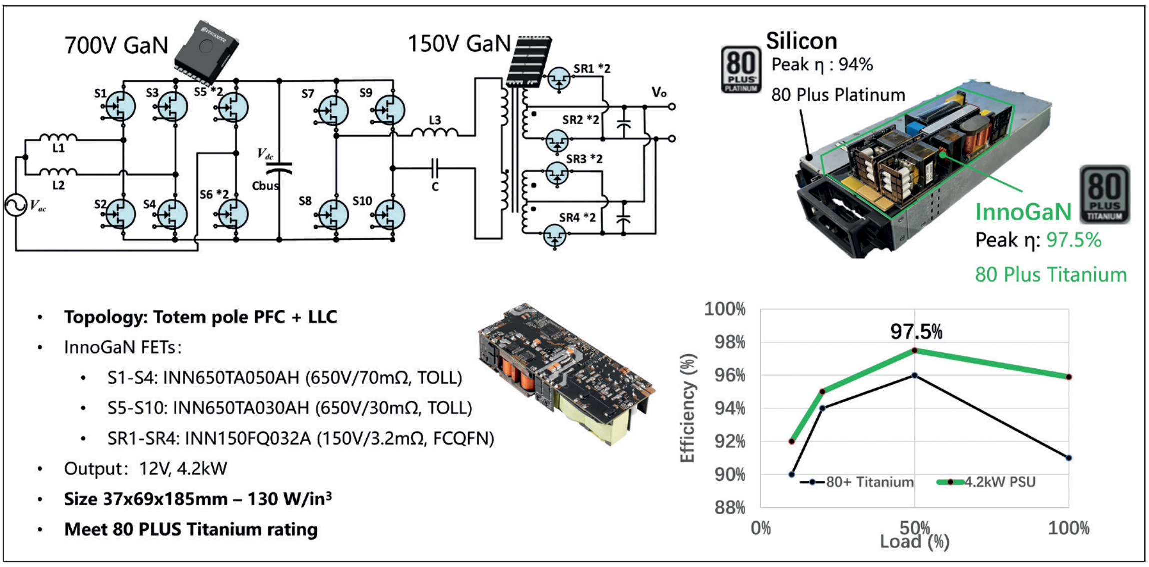
GaN devices, both discrete and integrated, are becoming more and more available targeting an ever-increasing range of applications.

BY DR DENIS MARCON, GENERAL MANAGER, INNOSCIENCE EUROPE

NOT SO LONG AGO, gallium nitride (GaN) technology was considered to be suitable only for specific applications in RF and microwave and other specialist markets. The first and still largest commercial usage of GaN for power switching applications is to be found in compact mobile phone chargers, where the emergence of the USB-PD standard and market pressure for sleek accessories created a demand for higher power density. It could be said that the GaN industry 'grew up' with this market, learning how to deliver large volumes of parts. But now the GaN industry is transitioning again with the emergence of a wide variety of GaN devices, both high and low voltage and – recently – by adding integrated solutions as well as discrete HEMTs.

It's probably worth spending a paragraph highlighting just what all the fuss is about. Simply, GaN delivers higher power, higher power density and greater efficiency with almost zero switching losses. This is mainly due to two factors. First, the accepted industry benchmark Figure of Merit, Ron Qg, is 10 times better than silicon. This means that systems can switch at a higher frequency without incurring any loss in efficiency. This gives designers the freedom to use smaller passives, which can result in reducing the overall BOM cost (more later). High efficiency also means that less heat is generated, so thermal management solutions such as heatsinks and fans can be eliminated or reduced in size.

The second aspect of GaN is that it has no body diode, and therefore the reverse recovery current is zero. This allows designers to select simpler power conversion topologies; for example, the totem pole bridgeless PFC design can be used instead of the more complex, larger BOM, dual boost bridgeless PFC circuit which would be necessary to keep efficiency high if the design was restricted to using even the best silicon MOSFETS.



➤ Figure 1: Astonishing power density specs can be achieved using GaN in both the primary and secondary PSU sides.

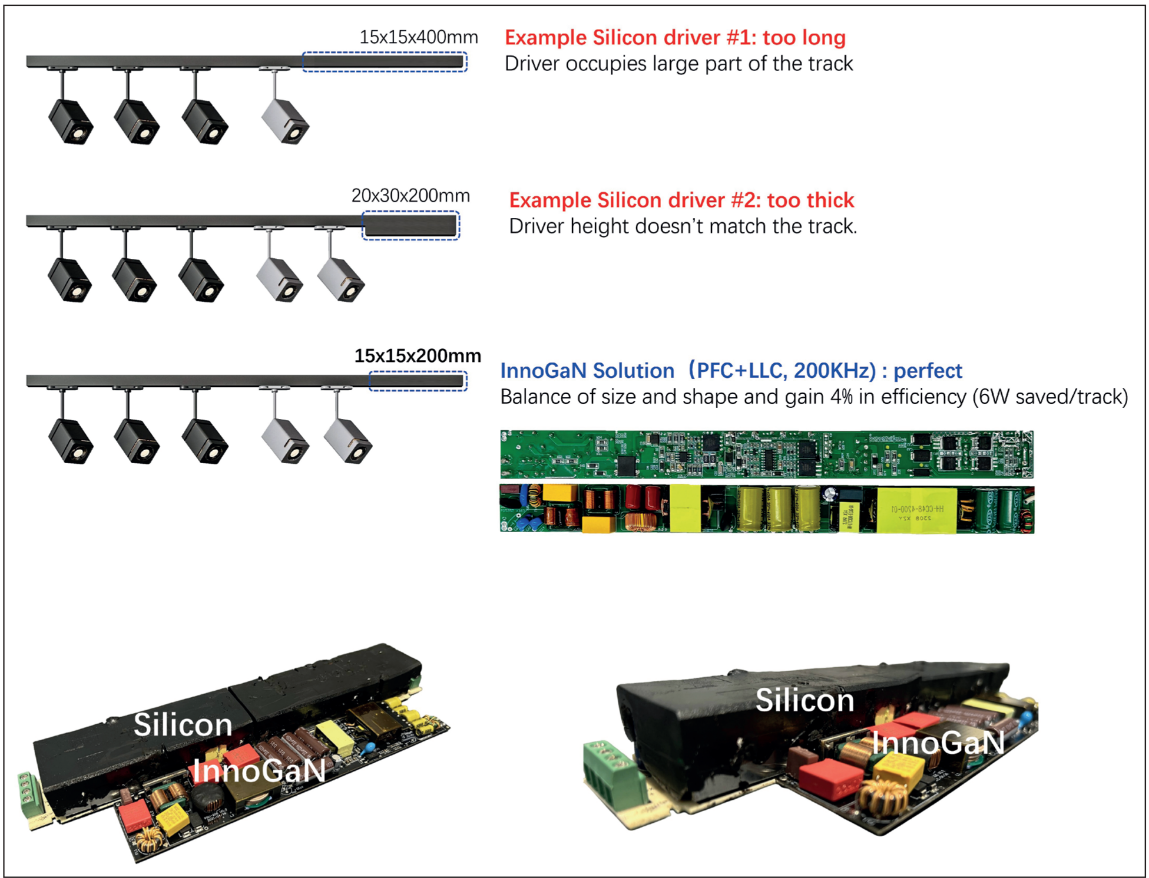


Figure 2: Using GaN results in a sleek design for LED driver and 6W power saving/track. At the bottom, a side by side comparison of a 200W GaN solution versus a 120W Silicon is reported.

In order for GaN to succeed in a wide range of application fields, industry needs a correspondingly wide range of GaN devices.

Innoscience, the world's largest 8in GaN-on-silicon integrated device manufacturer (IDM), now offers a very wide portfolio of GaN power devices covering low, medium and high voltage applications, with low voltage parts spanning 30 - 150V with ON resistances as low as 1.2mΩ. High voltage devices are available up to 700V with RDS(on) values between 30 - 600mΩ. These GaN FETs are also available in different packages including wafer level CSP to flip chip QFN with a top- or bottom-side side cooling DFN, TO- etc. By offering many standard packages, designers that are familiar with those packages from using silicon devices can easily switch to GaN. Also very recently, we have introduced a single- channel gate-driver optimized for GaN solutions.

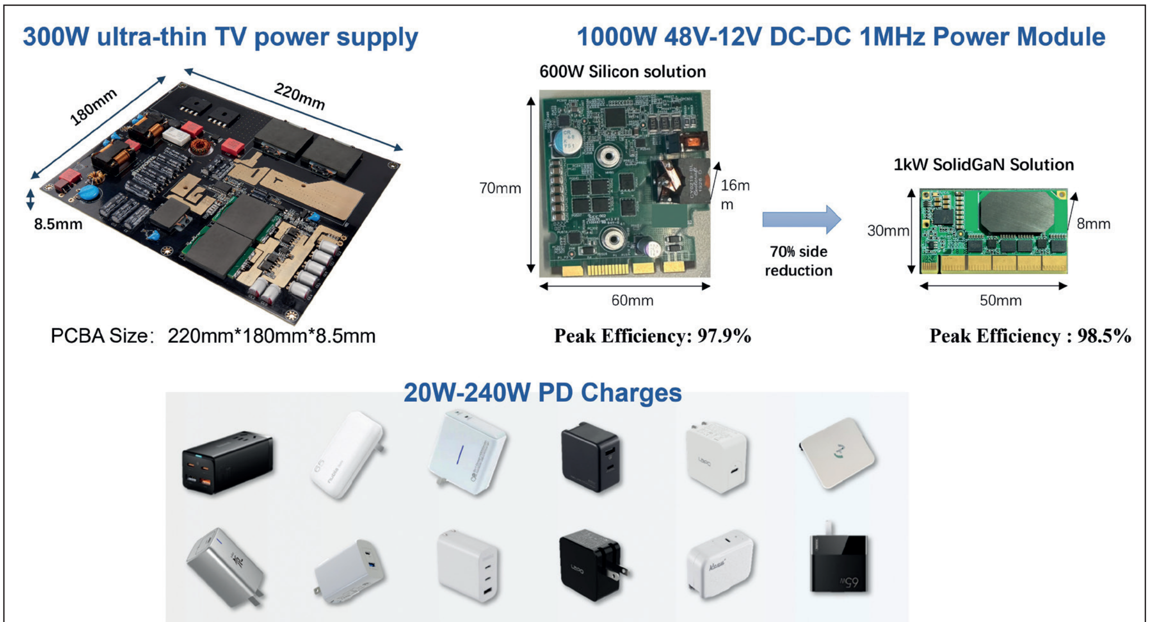
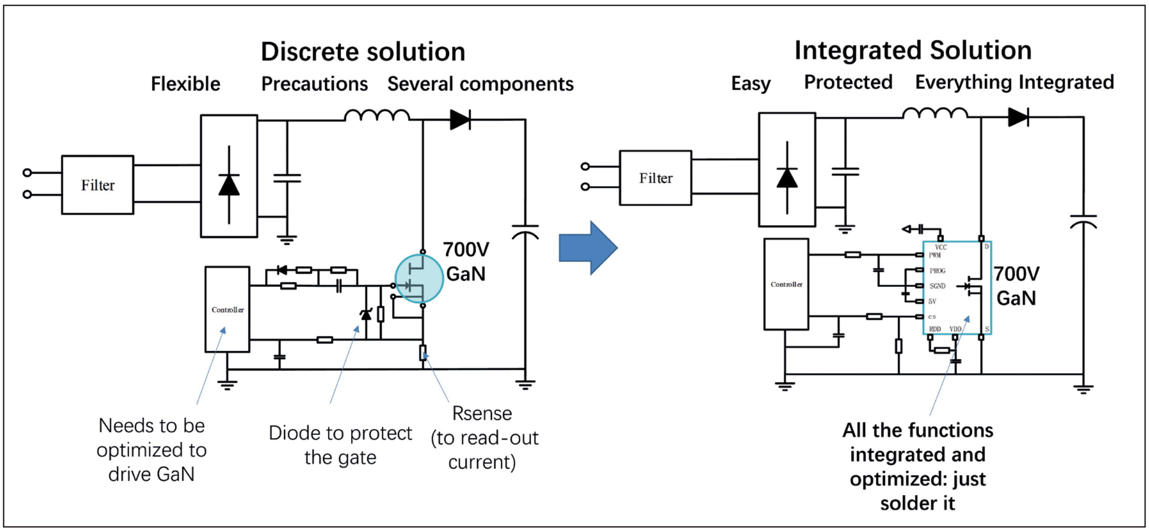


Figure 3: Many applications can benefit from GaN.



➤ Figure 4: The discrete GaN schematic.

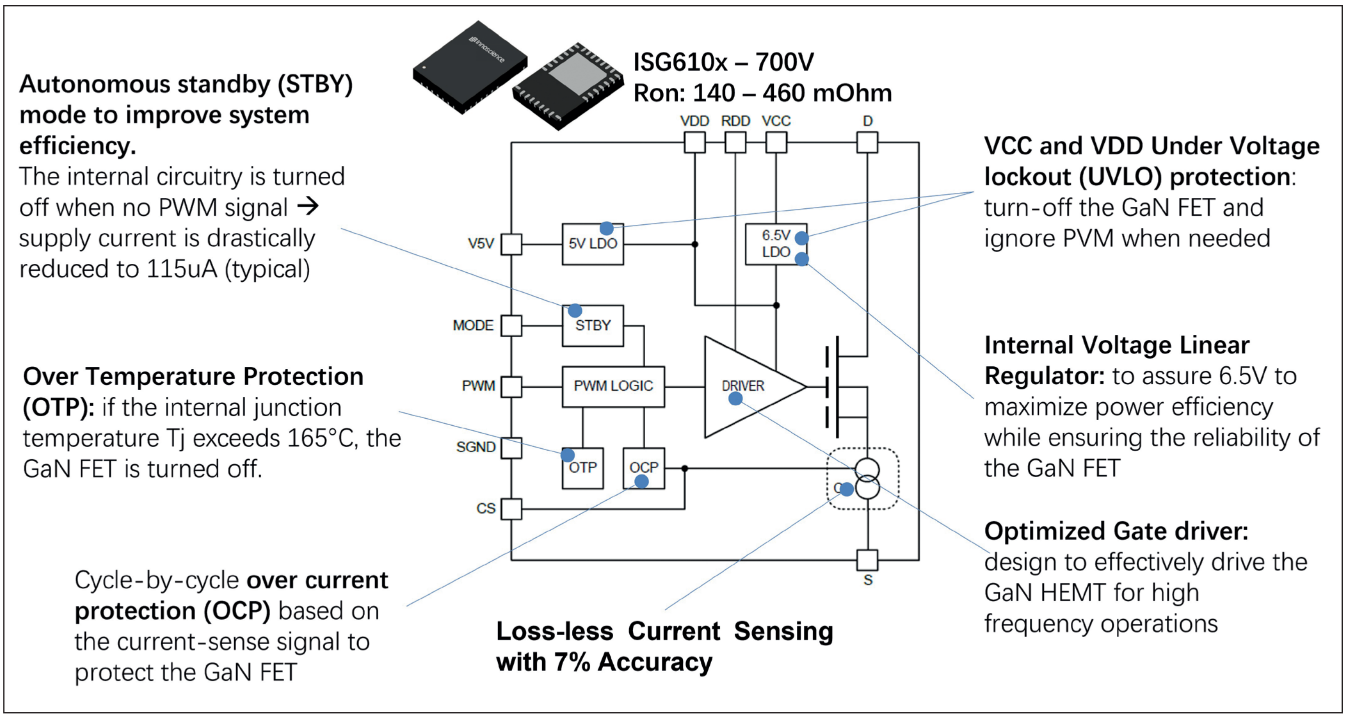
As an example of what can be achieved by combining low and high voltage GaN devices within a power supply unit (PSU) is considered in Figure 1. This example shows a 4.2 kilowatt PSU using a 700V high voltage GaN part on the primary side in combination with a 150V GaN device on the secondary side. The figure details a totem pole PFC plus LLC design using 30mΩ RDS(on) and 70mΩ RDS(on) high voltage GaN power switches in the TOLL package for the primary side; and for the secondary, four pairs of 3.2mΩ RDS(on) low voltage parts in a flip chip QFN package.

The result is a 4.2kW PSU that measures just 185 x 69 x 37mm and achieves an astonishing power density of 130 watts per cubic inch. It easily meets the 80 Plus titanium rating for efficiency, peaking at 97.5%. The equivalent PSU made using silicon could easily be twice the size.

Figure 2,F shows another application ideally suited to GaN. In a 150W tracklight, a silicon-based LED-driver is either too long or two fat. With GaN, you can have a 200kHz PFC plus LLC solution measuring 15 x 15 x 200mm that fits perfectly in the fixture. Plus, the Innoscience solution is 4% more efficient, resulting on a saving of 6W/track.

Moreover, a direct comparison of a 200W GaN solution versus a 120W Silicon solution is provided at the bottom of Figure 2, which shows that the GaN solution is 37% shorter and 57% thinner than a Silicon solution.

There are many other examples (Figure 3): a 300W TV, where a chunky power supply would spoil the profile of the otherwise slender unit, now powered by a GaN-based solution measuring 220 x 180 x 8.5mm; a 1000W DC/DC converter that is 70%



➤ Figure 5: New integrated GaN ICs from Innoscience are easy to use.

Whilst this is perfectly viable solution for many applications, Innoscience is introducing a range of integrated solutions for designers that say that they just want to use GaN and reap the benefits as simply as possible. SolidGaN devices combine power transistor, driver, current sense and other functions within a single, industry-standard QFN 6x8mm package

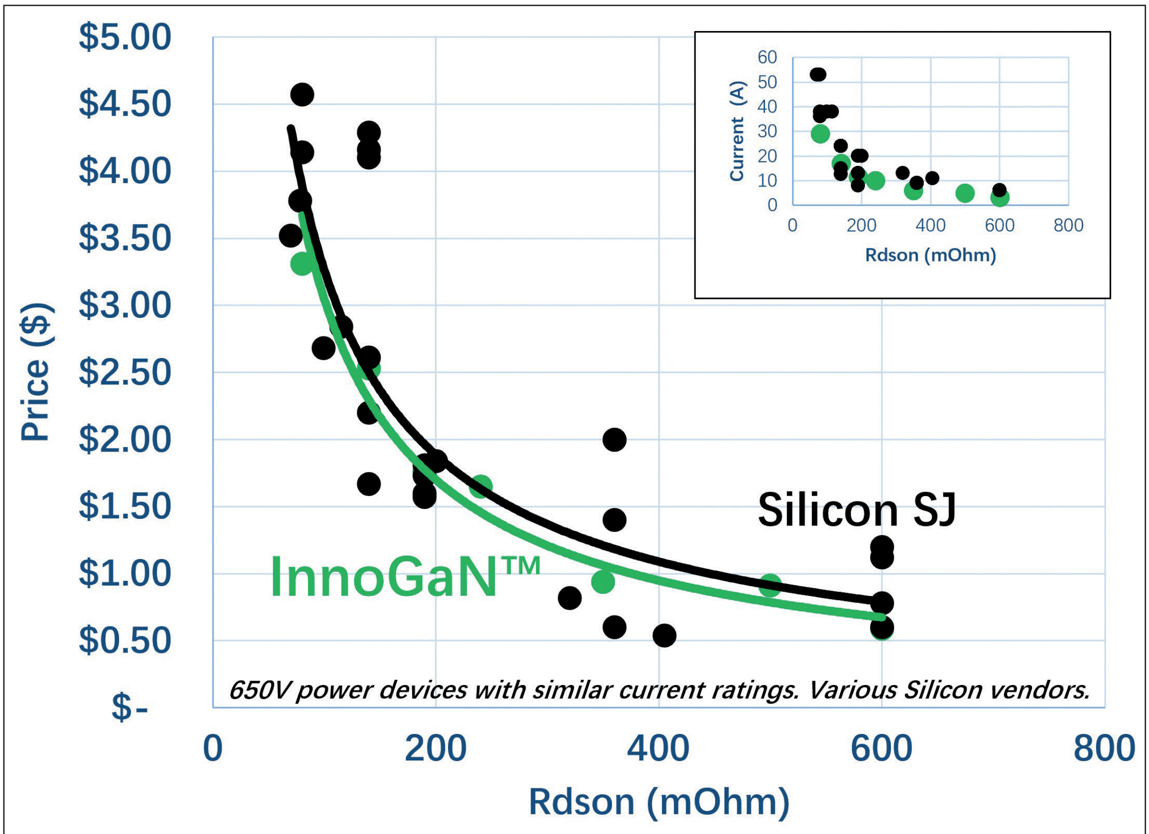
smaller and more efficient than a 600W silicon unit; the ubiquitous 20 – 240W charger designs; and many others for inverters, motor drivers, photo-voltaic solar power etc.

So far, we have only looked at discrete GaN solutions which are preferred by many engineers because of their design flexibility. However, using GaN does require some design know-how – which is readily available – as well as a GaN driver, protection circuitry and other components such as a sense resistor to read out the current (Figure 4).

Whilst this is perfectly viable solution for many applications, Innoscience is introducing a range of integrated solutions for designers that say that they just want to use GaN and reap the benefits as simply as possible. SolidGaN devices combine power transistor, driver, current sense and other functions within a single, industry-standard QFN 6x8mm package. The 700V ISG610x devices cover the range from 140 to 450mohm, and save PCB space and BOM count, while increasing efficiency and simplifying design for applications including USB-PD chargers, LED lighting, AC/DC and DC/DC power supplies and PFC, QR flyback, ACF, half bridge, and full bridge circuits. The integrated devices feature a wide 9-80V VCC range which is beneficial in USB-PD applications that require up to 28V output.

For low power operation, ISG610x family ICs also feature a low, 115µA quiescent current, thanks to an innovative automatic standby mode which is activated when the PWM signal voltage remains below VPWM_LO for a certain time period.

During this time, most of the internal circuitry is turned off, dramatically reducing energy wastage, enabling devices to meet the No-Load, Low-Load specifications of regulatory bodies such as ENERGYSTAR.



➤ Figure 6: Comparing the price of SJ devices and InnoGaN.

The loss-less current sensing with 7% accuracy of the new SolidGaN devices offers several benefits. Firstly, because the current sensing resistor loss is eliminated, a larger RDS(on) can be accommodated with no loss in performance, leading to cost reduction. Secondly component count is reduced and PCB footprint is minimized. Devices also feature a programmable switch turn-on slew rate to enable EMI to be minimised. An internal linear voltage regulator is included to assure a 6.5V supply, maximizing power efficiency while ensuring the reliability of the GaN HEMT. Finally, built-In under-voltage lock-out (UVLO), over-current (OCP) and over-temperature (OTP) protection are incorporated within the IC.

Price and reliability

With such significant benefits and wide availability in an ever-increasing device portfolio to match new application, one might be tempted to wonder why any design team would not make the move to GaN. The answer is simple, but based on outdated misconceptions concerning price and reliability.

Based on publicly available data, Figure 6 shows that Innoscience's InnoGaN GaN HEMTs are now price competitive with silicon. Furthermore, GaN offers the possibility to save further costs at a system level because the increased efficiency will lead to a reduction in size – and therefore price - of the passives and magnetic components that will be required.

Innoscience has managed to achieve price price-competitive GaN devices by investing in the world's largest 8in GaN-on-Si fabs, thus leveraging massive economies of scale. Also, by controlling all key manufacturing processes, including epitaxy, in house, the company is achieving consistently high yields.

If we now turn to reliability, the first point to make is that GaN may seem to be new, but on fact it has been around for over 20 years and is well studied and understood. Devices are now tested to the international JEDEC standard and to specific JEDEC guidelines drafted for wideband gap devices (JEP 180) where devices are stressed under switching stress to mimic real application usage.

Innoscience performs further extrapolated lifetime tests including HTGB (beyond max gate specs) and HTRB (beyond max off-state drain voltage specs).

Conclusion

GaN devices, both discrete and integrated, are becoming more and more available targeting an ever-increasing range of applications. With GaN devices power conversions and power management solutions can be made smaller, lighter, more efficient and simpler (less BOM). Devices are proven to be reliable, and – certainly with Innoscience's devices – there is no cost penalty to be paid by moving to GaN, quite possibly the reverse.

Navigating the next frontier of Wi-Fi 7 performance: rigorous RF, signalling, and throughput testing

In wireless communications, the advancement of Wi-Fi® 7 opens a new era of ultra-fast networks and reliable connectivity. Like other technological revolutions, they usually come with growing pains. The importance of comprehensive radio frequency (RF), signalling, and throughput testing cannot be overstated. Such testing is not merely procedural, but a critical step to ensure that Wi-Fi 7 can deliver its promised performance not as an individual device but as a network.

BY XIANG LI, INDUSTRY SOLUTION MARKETING ENGINEER AT KEYSIGHT TECHNOLOGIES

The Legacy of Wi-Fi 6 and 6E vs Wi-Fi 7: A New Benchmark for Excellence
Wi-Fi 6 and 6E set new benchmarks for wireless performance, significantly improving network efficiency, capacity, and speed. RF testing ensures the efficient use of spectrum and minimised interference while signalling tests verify the effective communication between devices and access points. Throughput testing, on the other hand, confirms that the theoretical speed improvements translate into real-world benefits for users.

Before the introduction of Wi-Fi 7 standards, Wi-Fi networks were never meant to carry massive numbers of devices. Manufacturers mostly focus on testing under non-signalling conditions, which means engineers can bypass the standard communication protocols and directly access the physical layer of the wireless device for testing. It simplifies the testing process and focuses on the raw performance. However, it ignores the fact that there could be hundreds of other wireless devices with complex environmental and channel conditions.

Wi-Fi 7 enables a massive number of devices for both industry and household users, such as phones, smart devices, IoTs, industrial IoTs, routers, range extenders and access points, and customer premise equipment (CPE). Wi-Fi 7 networks will offer distinct advantages in crowded settings, such as airports, stadiums, hospitals, and smart factories. Figure 1 and 2 show how complex the future Wi-Fi network will look. Ignoring the standard communication protocols and other network conditions is not a good idea if manufacturers want their Wi-Fi 7 devices to perform consistently and reliably.

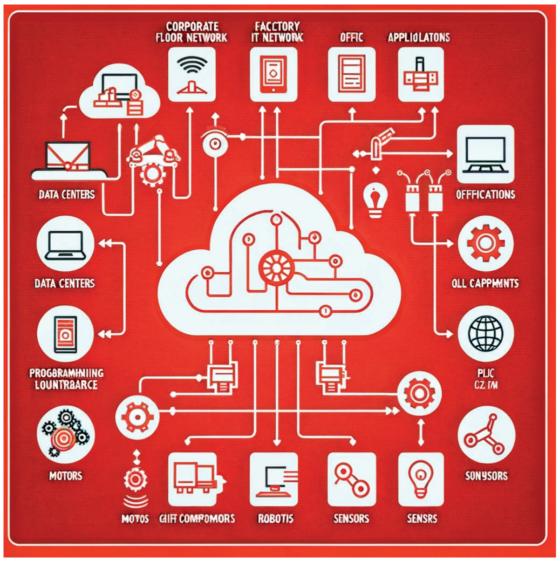


Figure 1. Smart factory with Wi-Fi-enabled devices

Not to mention, the Wi-Fi standard promises enhanced speed and efficiency by introducing advanced features such as 320 MHz channel bandwidth, 4096-QAM, and Multi-Link Operation (MLO). The complexity of these features requires a more systematic testing approach, one that can accurately simulate real-world environments and satisfy Wi-Fi 7 standards. Additionally, CPE is experiencing significant growth in popularity as cell operators are adopting 5G technology fast. This market expansion requires devices to have seamless transitions between Wi-Fi and cellular networks. Therefore, CPE manufacturers and network operators need to work together and run additional tests to ensure their products and networks are compatible with Wi-Fi 7 and 5G technologies.

RF testing with signalling: The foundational step towards excellence

Evaluating RF performance with signalling emulates how a device under test (DUT) operates in real-world conditions. Analysing the transmission (Tx) and reception (Rx) capabilities is essential for ensuring the device performs as end users expect.

In Wi-Fi development, for both access points (AP) and clients, it's important to start with RF performance assessment and then progress through the protocol layers. Any deficiencies on the RF layer can impact all subsequent tests at higher levels. RF testing enables isolation of the RF layer Tx and Rx operation.

Figure 2. Smart home with Wi-Fi-enabled devices

Transmitter power measurements

The transmitted power is a critical parameter that directly influences the performance and compatibility of the device in a wireless network. Capturing the boundaries for the maximum transmitted power output and the power envelope helps to reduce the risk of interference with other devices operating within the same frequency spectrum. This is particularly important in environments where multiple devices share the same band.

To accurately assess the performance related to transmitted power, engineers need to set up the AP or client device to operate at specific power levels. These levels depend on testing objectives, whether for routine evaluation or for diagnosing problems. Typically, tests involve operating the DUT at its highest or lowest power output during the most intense part of a transmission cycle. This approach is designed to push the device to its operational limits, thereby uncovering any potential weaknesses or failure points.

For precise measurements, the DUT is often connected directly to the testing equipment via wired cables, which helps to avoid the inaccuracies and variables introduced by over-the-air (OTA) transmission. By using a direct connection, engineers can capture more reliable and controlled measurements, leading to a clearer understanding of the device's performance.

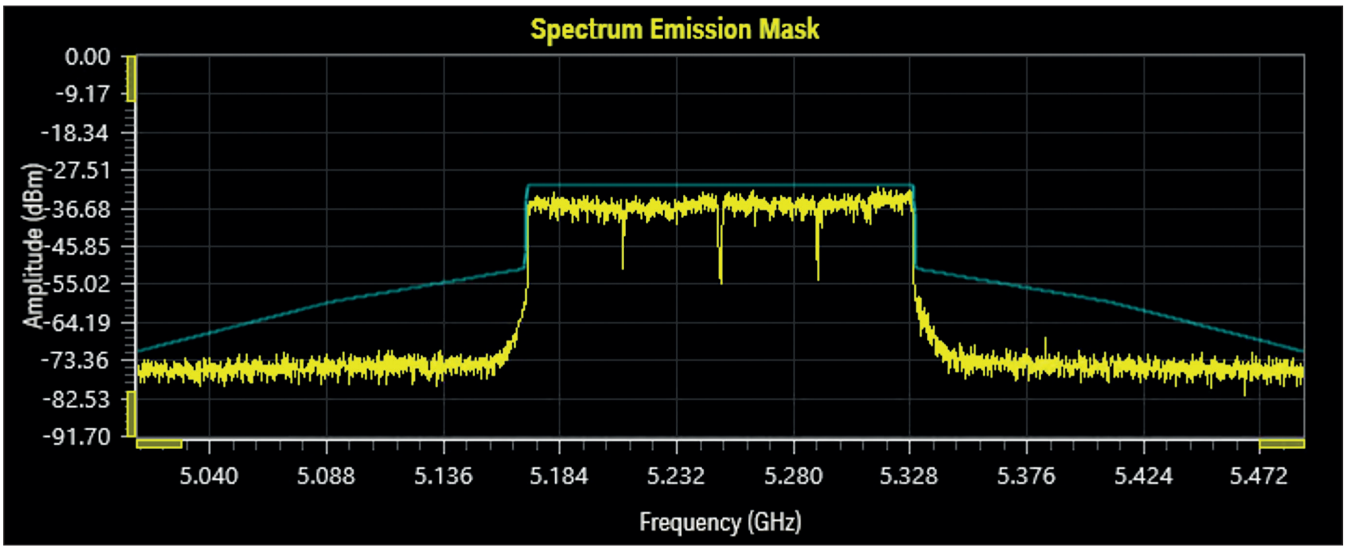


Figure 3. Example of a spectrum mask

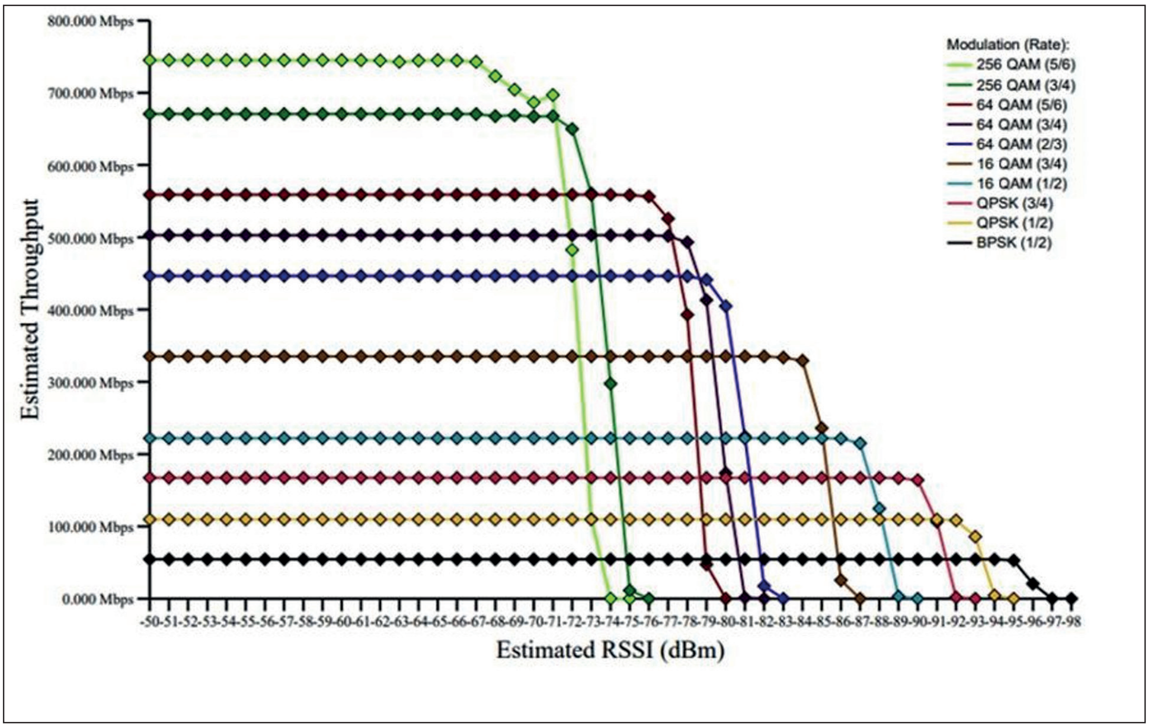


Figure 4. Estimated throughput vs estimated Received Signal Strength Indicator (RSSI)

The measurement of the transmit spectrum mask is a critical process. It outlines the energy profile across different frequencies. An example is shown in Figure 3. By establishing specific thresholds at various segments of the signal, a defined spectral envelope is created for the DUT. That means the operating frequency of this DUT must fall within the envelope to prevent unwanted interference and ensure sufficient power delivery. This is important for both APs and clients.

Maintaining stability during transitions, such as during burst transmissions or when switching frequencies, is crucial to ensure the integrity of the signal's transmit spectrum mask. A common issue encountered is the occurrence of an unexpected, narrow burst of power during a period of inactivity, or the 'off' phase. Such bursts might result in unintended signal leakage during periods of transmission. Alternatively, these issues may arise during the process of frequency conversion, known as 'images'. These challenges highlight the importance of testing and optimising device design to prevent such irregularities, ensuring consistent performance and compliance with established spectral standards.

Transmitter modulation quality measurements
Modulation quality is another key metric to measure. It's about maintaining high signal quality when implementing different signal patterns to reduce errors. As mentioned before, Wi-Fi 7 employs 4096 QAM as well as 1024 QAM from Wi-Fi 6. It increases the importance and difficulty of modulation quality measurements.

For this measurement, the test setup is the same as the power measurement. There are two main behaviours engineers need to check: the distance from the ideal signal points (error vector magnitude) and the accuracy of each modulation point (constellation diagram). If the points on the chart are not where they should be, it means there is background noise or jitter in the signal's timing.
Transmitter spectral quality measurements
Measuring how well a Wi-Fi design performs across different frequencies is crucial for smooth operation and reducing interference. Spectral flatness and occupied bandwidth (OBW) are the main parameters for measuring spectral quality.

When a Wi-Fi signal doesn't operate at its expected frequency, it can cause signal leakage and interfere with other transmissions. Also, it will cause issues with burst time and envelope of a Wi-Fi design. Common problems include unwanted signals, distortions, or harmonics, often due to bad grounding, ineffective noise control, or errors in frequency conversion.

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Receiver PER measurements

Understanding the characteristics of the receiver is also important to ensure devices not only capture but also accurately decode the received signals. To evaluate the performance of a receiver, engineers assess how sensitive the receiver is to different signal strengths, the receiver's ability to handle data efficiently at the highest signal strength it can receive, and performance in terms of packet error rate (PER) and rate versus range (RvR).

Focusing on the receiver's PER involves examining the precision with which it processes incoming packets. The PER metric reflects the proportion of accurately received packets out of the total received, serving as a key indicator of the receiver's reliability. Reception errors and difficulties in decoding signals can compromise the accuracy of the information relayed to the user, potentially leading to connection issues.
Factors such as suboptimal receiver sensitivity or decoding inaccuracies can deteriorate the PER, highlighting areas that may need improvement to ensure optimal receiver performance.

RvR examines rate (transmitted data throughput) versus range (over distance). The DUT is connected to a reference client or AP through a variable attenuator. For each increasing decibel (dB) step of the attenuator (increasing path loss), traffic runs from the DUT to the reference device, and the rate is recorded. RvR is often misunderstood as a test of Tx RF quality, but instead best serves to isolate and allow assessment of transmit rate adaptation.

As the simulated distance increases, the device must reduce its rate to adapt the (modulation and coding schemes) MCS, allowing data transmission with higher path loss and lower signal-to-noise ratio. Each distance has an optimal MCS choice of transmission. In practice, rate adaptation inefficiency will cause lower throughput, higher latencies, and degradation of application quality of experience.

Receiver sensitivity measurements

Receiver sensitivity determines how well a Wi-Fi device can pick up and interpret signals across various power levels and MCS. This sensitivity test also finds the level at which the receiver can no longer process the signal.

To assess receiver sensitivity, a network emulator with a signalling mode sends out Wi-Fi signals at decreasing power levels, starting from the highest.

This continues until the point where the receiver fails to recognise the signal. Plotting these results visually is an effective method to pinpoint where the receiver's sensitivity starts to decline.

See an example in Figure 4. This process benefits greatly from automation, especially when evaluating the packet error rate (PER) against power levels across various MCS rates and device settings.

Conclusion

As we move closer to fully realising the potential of Wi-Fi 7, it becomes evident that the RF, signalling, and throughput tests are not merely procedural checkpoints but the pillars of excellence in wireless communication. The seamless interplay between Wi-Fi and 5G in customer premises equipment outlines a future with a multitude of devices in diverse ecosystems.

The various test measures, from transmitter power to receiver sensitivity, contribute to ensuring Wi-Fi 7 devices perform at their peak in any environment, which directly reflects in the end-user experience. This comprehensive testing paradigm fortifies the foundation for a new benchmark in Wi-Fi performance, fostering connections that are not only faster and more reliable but also smarter and more intuitive than ever before.

Enabling test automation in new power electronics reliability

Test automation is critical for optimizing reliability testing of power semiconductor devices during all stages from R&D to manufacturing.

BY ANDREA VINCI, SENIOR TECHNICAL MARKETING MANAGER AT TEKTRONIX

THERE IS NO SUCH THING as a univocal meaning and definition for "reliability" testing. The definition I like the most is this one: a methodology to discover how to improve product quality, enabling you to verify whether your device can withstand all possible stresses it will face once marketed into a customer's application.

There are several development stages where reliability testing is critical: the R&D (Research and Development) phase, the pre-production (small quantities) phase, and in the mass production phase. In R&D, it is important to ensure that the characteristics and reliability defined in the design phase are met. In Pre-Production, the mass production line is used in limited lot sizes to evaluate and exclude problems before mass production commences.

The Bathub Plot

Ask reliability engineers to draw a function on a graph, and they will certainly come back with a bathtub curve like the one in Figure 2; the curve depicts a number of temporal regions for device failures.

Depending on the product lifecycle stage, reliability tests can present different challenges, methodologies, intrinsic constraints. Mainly, they will reveal different failure modes. You refer to an "extrinsic" reliability indicator when you test robustness against failures related to defectivity and process variability, causes that are external to the real capabilities of the design and materials.

You refer to an "intrinsic" reliability of the compound semiconductor when the failure is related to how the

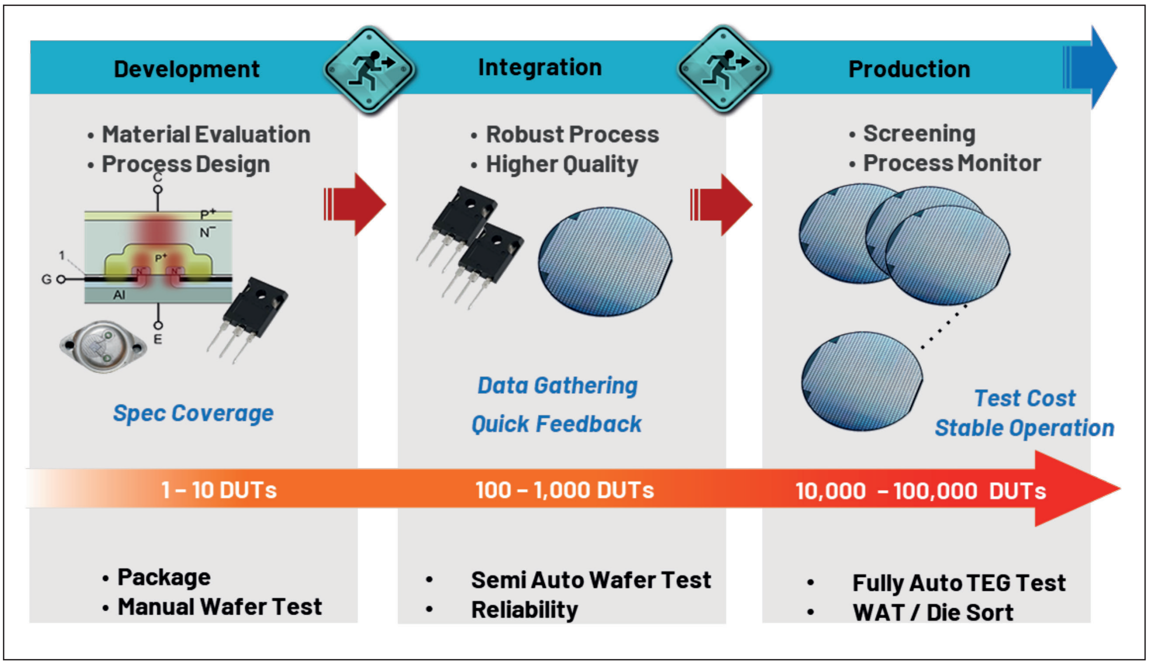


Figure 1: Semiconductor product development phases

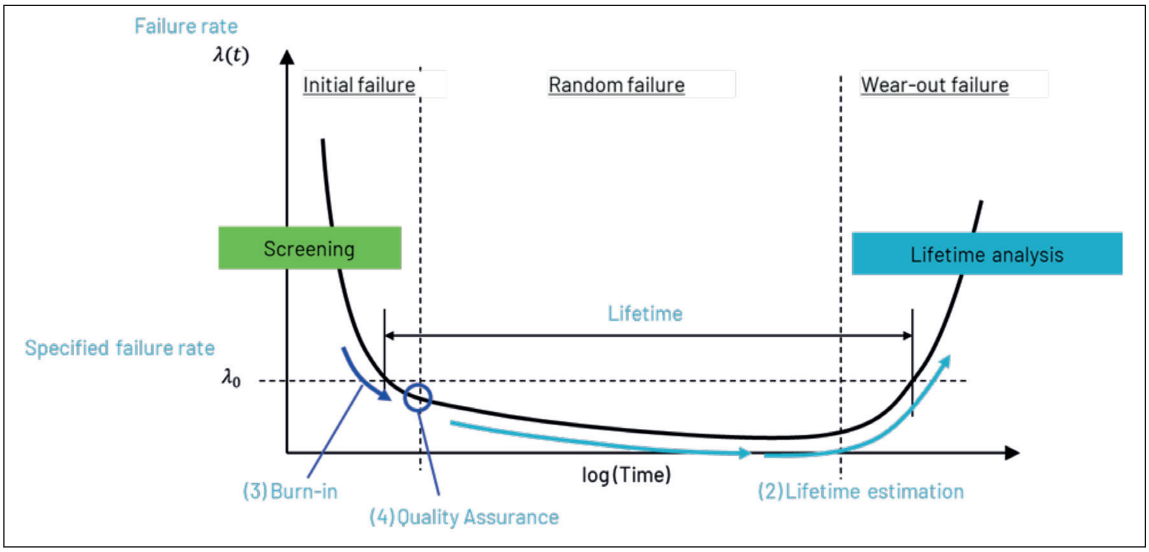


Figure 2: The Bathtub Plot

component is designed (device structure, materials, and their wear out).

In summary, devices need to be stressed to failure and failure modes, analyzed as well as categorized as either extrinsic (early life failure) or intrinsic (wear-out failure). When you will have fixed the extrinsic failure causes, then primary failures will be due to intrinsic sources; this is when you need to model how the wear-out occurs. The degradation model will help you to predict lifetime and failure rate.

We all agree it is really not possible to wait years to study how a new technology-based compound semiconductor device can fail. To accelerate a potential failure mechanism, an enhanced stress is applied to devices, which, in the case of WBG power semiconductor devices, can mean stressing current, voltage, temperature, humidity, mechanical vibrations etc. Applying specific degradation models is the way to predict failure rates under stated stress conditions and lifetimes.

Meeting application related standards

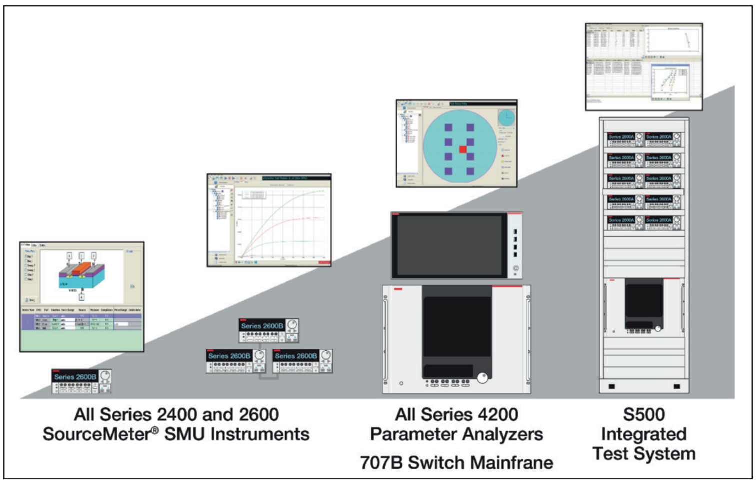
Everyone agrees today about how wide bandgap (WBG) semiconductors like SiC and GaN, thanks to their superior electrical and thermal characteristics compared to silicon, have enabled the transformation of electricity use especially for power electronics switching applications. They are the de-facto building blocks of power converters in use across electrified mobility market, data centers, renewable energy and electric grids etc. When used in high-voltage, high-power or high-temperature conditions, all new switching devices experience electrical and thermal stresses because of high electric fields and high currents generated during their operation. New technologies like WBG can demand more extensive and accurate approached than standard guidelines.
Every market, depending on its specificity, demands component suppliers to guarantee specific operation conditions. As previously stated, manufacturers do this by testing devices extensively for reliability. The approach to guarantee reliability is to follow application specific guidelines and standards.

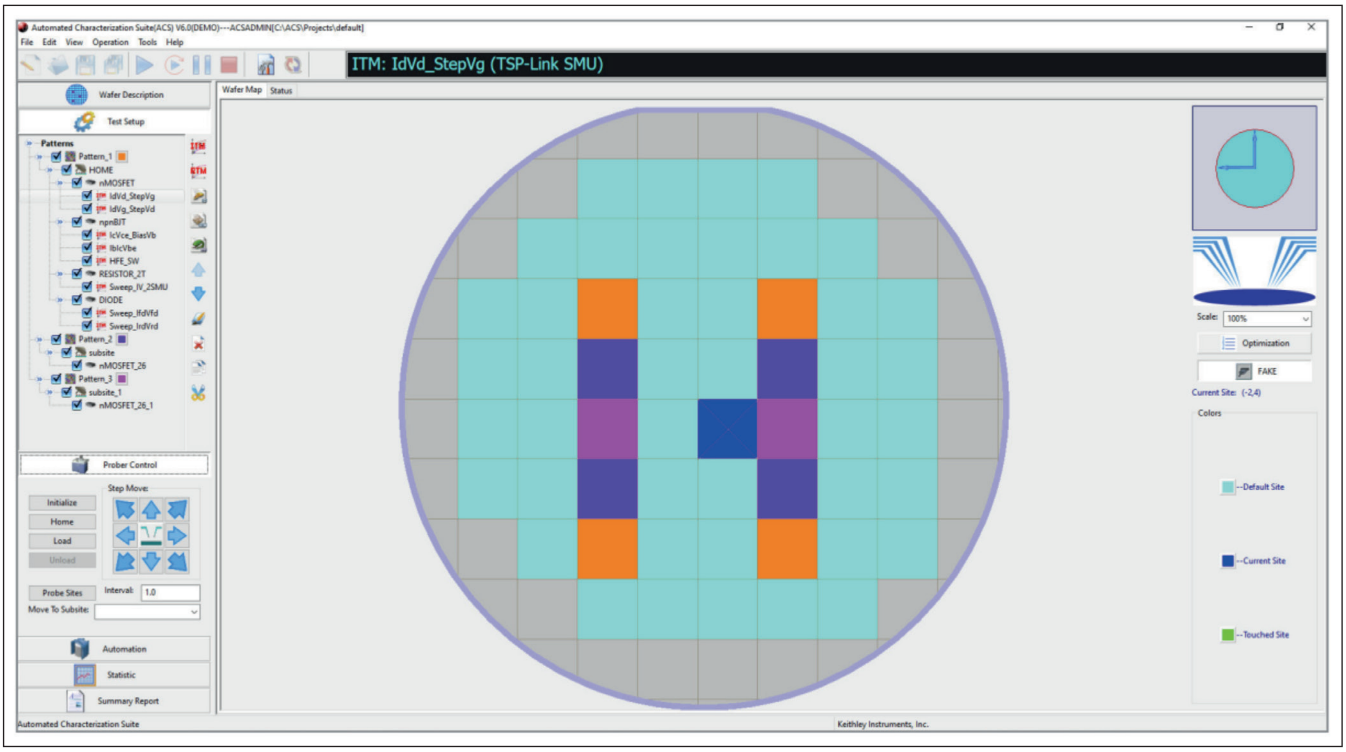
There are reliability assurance guideline for space applications applying to compound-semiconductor such as GaAs, which are typically used in that Industry. In contrast, the automotive industry typically uses SiC discrete MOSFETs; to qualify them at their determined operating voltage levels (e.g. 1200V or 1700V) and max operating temperature levels (e.g. 175 °C or above) suppliers must follow the Automotive Electronics Council AEC-Q101 standard guideline. Other standards like JEDEC are for industrial use of the component's qualification, MIL-STD-xx for military and so on.

Approaching new technologies adoption

Failure mode scenarios for new compound-semiconductors based power electronics can be multiple and complex, and all need to be addressed to ensure a very low failure rate percentage with significantly high statistical confidence. The so-called physics for failure analysis is getting increasingly complex with wideband gap materials as are predictions on their behavior under extreme

Figure 3: From lab to fab with same equipment building blocks





➤ Figure 4: ACS standard suite for interactive probe station control

environmental conditions. Qualification tests where accelerant stresses are applied have different names.

HTRB stands for high-temperature reverse bias test; this test aims to analyze failure related to DC bias stress of Vds on a MOSFET. TDDB stands instead for time-dependent dielectric breakdown; it is a failure mode that can occur when a conduction path is formed by an overlapping of defects generated in the dielectric of the MOSFET.

A GaN HEMT is usually under a high forward bias voltage stress which is not only DC but also AC. AC stress shows longer breakdown times than under DC stress and it varies a lot with higher switching frequency condition, temperature, etc.

Taking these tests in an exhaustive way requires the running of hundreds of thousands of hours of testing, each with tens of thousands of temperature cycles and humidity points. Post qualification, semiconductor manufactures still need to accumulate millions or trillions of hours data to acquire a failure in time (FIT) rate in the field.

We then need reliable and accurate measurement logging to complete our lifetime prediction modeling and release the fundamental calculation called mean time to failure (MTTF), which is the output of a prediction modeling algorithm fed by data obtained with test methodologies like the TDDB.

Time invested on reliability testing can be significant. Test execution speed and amount of information on reliability to be obtained need to be balanced, and deciding what to prioritize as the most important is difficult

The ask to T&M supppliers

Test and Measurement Suppliers equipment must meet the need of customers to follow ever more demanding standardized methods for performing reliability testing and failure analysis at the packaged device level,; as well as within manufacturing where these tests are run at wafer level.

In both contexts, factors like testing time and measurement capabilities directly correlate to production capacity, testing cost and material loss if the packaged device fails;the optimization process of testing closely relates to the ability to evolve test automation. Semiconductor manufacturers producing high quality devices seek suppliers of reliable sources, to apply the electrical stress in both static and dynamic conditions, and accurate measurement at the same time remarkably high or extremely fast, or both dv/dt or di/dt. Reliability test infrastructure needs equipment capable of sourcing voltage and current ranges at the highest testing capacity but with the minimum cost and requirement on the sourcing equipment. Precision is accuracy and repeatability in both the parameter adjusting, cycle after cycle, and measurement.

Further need is to continuously monitor and display measured thermal and electrical signals, providing an easy to configure control panel to quickly upload electrical and thermal stress scenarios with the minimal cost of ownership for data acquisition and monitoring systems.

A real packaged device reliability use case scenario

How do you account for the longer potential lifespan of SiC based devices? They are subjected

to as much as ten times the operating voltage as their silicon predecessors, and likely operate in high temperature environments. Typical SiC MOSFETs reliability tests involve stressing a batch of sample devices for hundreds or thousands of hours with bias voltages, that are greater than or equal to their normal operating voltages, while subjecting them to temperatures that are well beyond normal operating conditions. During this stress, a variety of key operating parameters are measured at specific time intervals. Changes in device performance may indicate a defect in the part, allowing it to be pulled for failure analysis before it gets to the end user.
A multi-channel, programmable power supply can be used to power and stress the device.
The channels of the power supply can be routed together in series, or parallel, to increase the voltage or current output of the supply. Programmable power supplies, that have sweeping functionality, allow you to customize the stressing routine to fit your testing needs. Batches of devices can be connected in parallel to a single supply to increase test density.

On the measurement side, DMMs provide options to choose the level of accuracy and resolution that you need with either a 6½-digit or 7½-digit meter, but also have switching capabilities, increasing the number of devices that can be tested at a given time and decreasing overall test time. Multi-channel DMMs are great tools to monitor temperature, as well, during temperature-controlled tests.
Software that controls the whole solution can ease integration and setup by automating the process.
The software should be able to collect data for extended periods of time, ensuring you can view trends in the devices.

Keithley's KickStart Software ties the whole solution together, with intuitive controls and long-term data collection.

Keithley KickStart software can control and configure each of the power supply channels individually, output a constant bias voltage for stressing or customize the output sequence using the list sweep function. The sweep points can be defined directly in KickStart software or by importing a ready-made CSV file. The time for each point in the sweep is controlled by the list hold time setting. Setting this to Points sets up several measurements to take per step in the sweep. Changing this setting to Time allows you to set a custom dwell time in seconds for each step, truly customizing the stress sequence applied to the device.

A real wafer level reliability use case scenario

Let us now consider the case of testing before device packaging occurs, hence at wafer level. Engineers need to deploy tests such as charge trapping, NBTI enhanced hot carrier and TDDB enhanced NBTI. Measurement methodology requires DC stress and measurement to a point where both DC and pulse stress are used to study degradation relaxation effect.

Keithley instrumentation ranges across the 4200A-SCS device characterization system Keithley 2600 Series and 2400 Series SMUs, ultra-sensitive current sources and nanovoltmeters, switching and data acquisition systems.

These building blocks are easy to integrate into existing reliability, technology development, and semiconductor labs, incorporating them into a self-contained and fully automated test system.
Many of these instruments come with Test Script Processor (TSP®) and TSP-Link® technology for ultra-high-speed operation and parallel test, enabling the instrument to perform advanced tests without PC intervention using embedded test scripts and complete test subroutines.

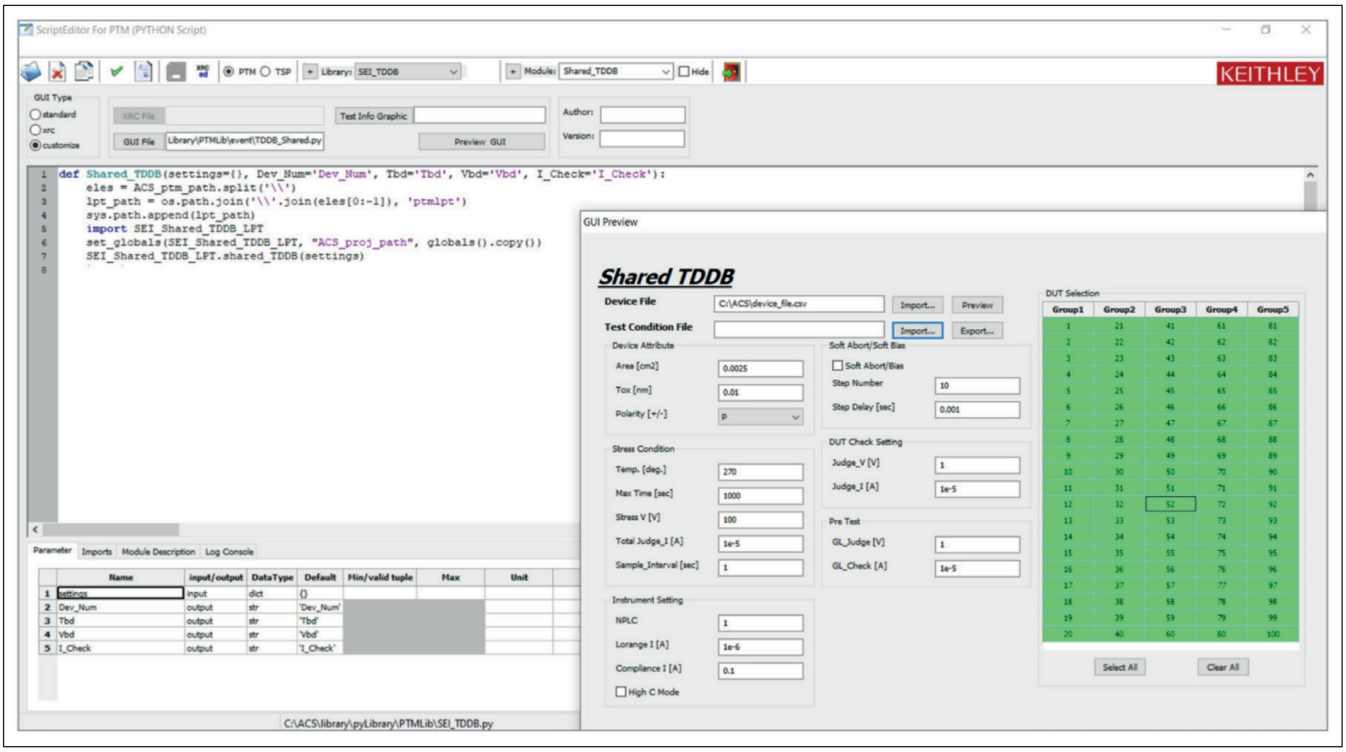
Keithley instrumentation includes a comprehensive device characterization suite called ACS (Advanced Characterization Suite); this software supports component characterization testing of packaged parts and wafer-level testing using probers.

The software embeds generalized libraries, functions, and demo projects to support the Shared Stress Reliability Test Application. Test libraries based on JEDEC Standard (e.g. JEP183A for the Power MOSFET SiC Reliability test) are included as well.

At the wafer level, Keithley's ACS integrated test systems feature a Wafer Description Utility and wafer map. Users can easily build wafer description files with integrated test plans. Color-coded wafer maps are updated in real-time during test execution to show pass/fail metrics, providing clear visibility into test results and assuring that test outcomes will be productive.

There is interactive prober controller to control wafer movement during test development to validate test setups on actual structures and during lot disposition to navigate to a problem area of the wafer and execute testing manually. ACS supports

Keithley instrumentation includes a comprehensive device characterization suite called ACS (Advanced Characterization Suite); this software supports component characterization testing of packaged parts and wafer-level testing using probers



➤ Figure 5: Python script for time-dependent dielectric breakdown (TDDB) analysis

control of FormFactor, MPI, Electroglas, TEL and ACCRETECH, Signatone, Semiprobe, HiSOL and other probers.

ACS includes test routines such as macros, scripts, and custom GUIs. You can control any Test Script Processor (TSP™) instrument using a script test module (STM) script, but also using the Python language test module (PTM) script, including instrumentation from other vendors.

To increase throughput while minimizing costs the system supports shared stress testing in ACS software v6.3, allowing users to apply different reliability test methods such as TDDB, AC-TDDB, TZDB, and HTRB to large groups of DUTs in parallel. A switch matrix is used to control when stress is applied to the DUTs and when measurements are taken.

A typical SiC MOSFETs reliabliity issue

JEDEC standard JEP183A introduced guidelines for measuring the threshold voltage (Vt) of an N-channel vertical structure SiC MOSFET device. This was because SiC devices present in general an higher instability of Vt compared to Silicon. The standard aimed to identify measurement methods and propose preconditioning guidelines to minimize the effect of Vt hysteresis.

This hysteresis phenomenon is mainly caused by hole charge trapping occurring when sweeping the gate device upward and downward. The JEP183A standard proposed then a new guideline to measure threshold voltage in a more consistent way. The idea is to add a pre-conditioning pulse prior to the gate sweep measurement to release any trapped hole charges from the silicon oxide interface and sweep downward. The JEP183A standard also proposed three different methods of SiC threshold measurement.

Keithley systems based on SourceMeter® units (SMUs) implement this threshold voltage test on SiC Power Mosfets devices. SMUs and software can support all three of the methods proposed by the JEDEC standard. The procedure with pre-conditioning pulse and sweeping can be easily done by TSP scripts to run on instrument or that can be embedded in ACS-Standard and ACS-BASIC software, giving the user the benefit of ACS's graphical interface so code modification is not necessary.

Conclusion

Test automation is critical for optimizing reliability testing of power semiconductor devices during all stages from R&D to Manufacturing.
For maximum system speed and programming simplicity, the Keithley TSP-Link® intercommunication bus allows multiple building block instruments to trigger and communicate with each other. Keithley Test Script Processor (TSP) technology enables all instrument control and most data management to be performed at the instrument level, eliminating the typical LAN traffic delays that slow system-level throughput in instrument-based systems.

ACS software provides all the tools required for shared stress reliability testing and makes automating the tests easy. Along with embedded projects, a new PTM (python test module) library and linear parametric test library (ptmlpt) have been implemented as well. The PTM can be modified by the user as needed, showing that ACS software offers the flexibility to support almost any reliability test application.

Silicon-based semiconductors: **Powering ahead**

Silicon-based semiconductor technologies, such as power MOSFETs and IGBTs, are essential in every modern power electronics system and play a crucial role in controlling and converting electrical energy. Due to their unique physical properties, these specialized electronic components are designed to handle high voltages and currents, providing benefits and advantages in many different applications, such as renewable energy systems, electric vehicles, power supply for data centres and industrial machines.

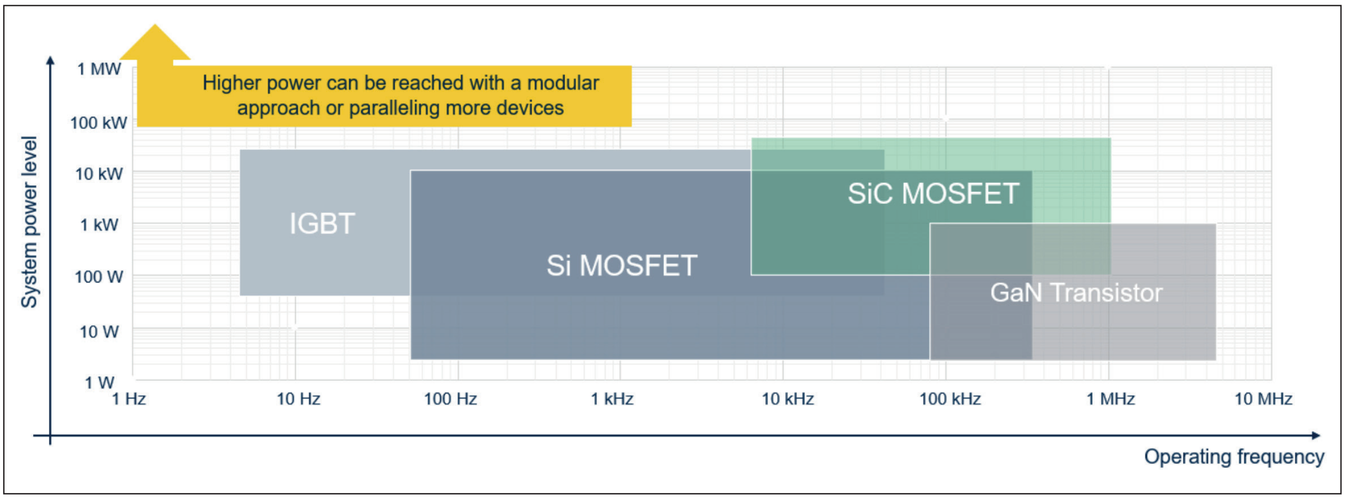
BY ANTONINO GAITO, POWER TRANSISTOR SUB-GROUP, TECHNICAL MARKETING MANAGER, HIGH VOLTAGE DIVISION, STMICROELECTRONICS AND CARMELO FINOCCHIARO, POWER TRANSISTOR SUB-GROUP, MARKETING ENGINEER, STMICROELECTRONICS.

A POWER MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) is a type of Field-Effect Transistor (FET). Applying a voltage to the gate terminal, a current will flow through the channel from the drain to the source.

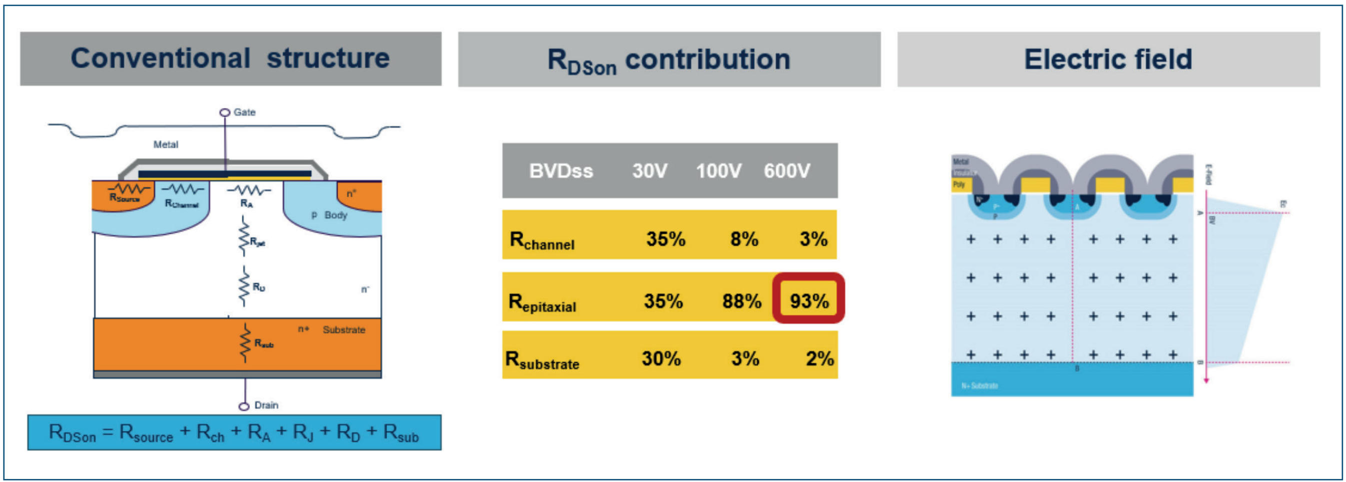
Among the main parameters which affect the most performance of a MOSFET, there are the drain-source resistance RDSon, the gate charge Qg and the breakdown voltage BVDss. In terms of efficiency, lower RDSon means lower conduction losses and higher efficiency in applications where MOSFETs are used to switch current on and off. Lower RDSon also means less heat will be generated during operation, which can reduce the need for heat sinks and other cooling mechanisms. In high-frequency applications, the switching losses might become more significant compared to conduction losses, but having a low RDSon is still beneficial for the overall device performance.

A lower gate charge allows faster switching speeds, and this is advantageous in high-frequency applications. When a switch commutes, power is dissipated in the form of heat. A lower gate charge can reduce these losses, improving efficiency. The gate charge also determines the current needed from the gate driver to switch the MOSFET at desired speeds. Lower gate charge can lower the requirements on the gate driver circuit.

The breakdown voltage helps determine the maximum voltage that the system can handle. MOSFETs must be chosen with a breakdown



➤ Figure 1. Power transistors technologies



BVDss	30V	100V	600V
$R_{channel}$	35%	8%	3%
$R_{epitaxial}$	35%	88%	93%
$R_{substrate}$	30%	3%	2%

Figure 2. Planar MOSFET technology

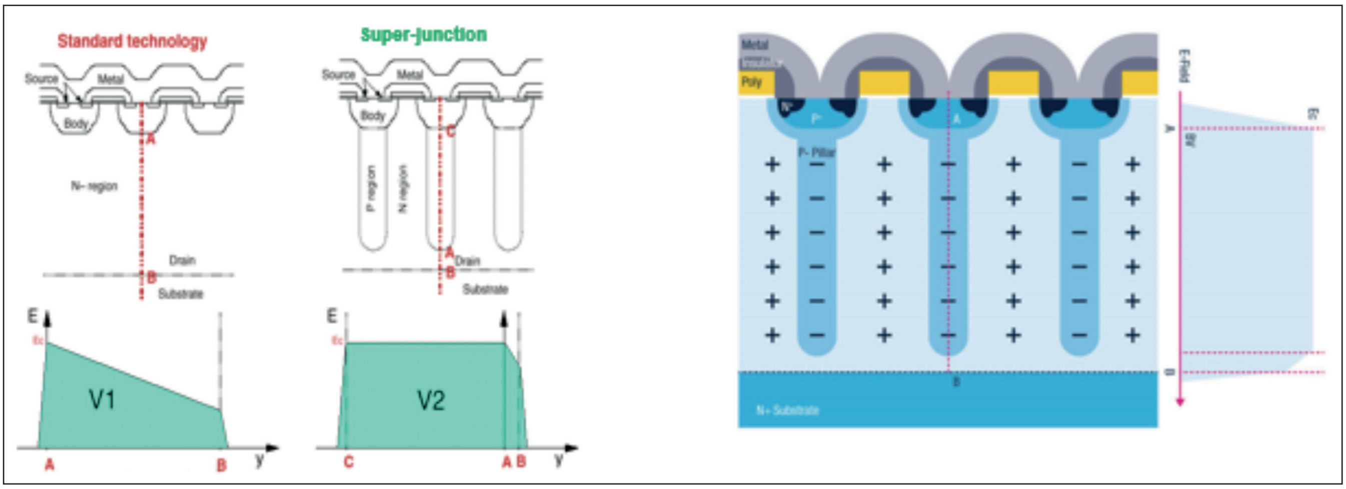
voltage higher than the maximum voltage expected in the application. A higher breakdown voltage also provides a larger safety margin, improving the reliability of the MOSFET under transient conditions. Power systems often experience voltage spikes, and having a sufficient breakdown voltage helps protect against these transients. The evolution of silicon MOSFETs from planar to superior structure technology represents a significant advancement in semiconductor design. Planar MOSFETs have a simple structure and are cost-effective for low-power applications, but they face limitations in terms of voltage scaling and drain-source resistance.

A super-junction MOSFET is designed with a more complex structure that includes a series of p-type and n-type regions that are alternately stacked vertically in the drift region, between the gate and the drain. The key factor of the super-junction design is the charge balance between these p-type and n-type regions, which allow for much higher doping concentrations while maintaining the breakdown voltage at the same level. Due to the higher doping levels and the charge balance, super-junction MOSFETs have significantly reduced drain-source resistance compared to that of planar MOSFETs with the same voltage rating. These characteristics enable the ability to handle higher voltages without increasing the physical size of the device, leading to higher efficiency, especially in high-voltage applications. The manufacturing process for super-junction MOSFETs is more complex and requires more precise control than that of planar MOSFETs. Planar MOSFETs are often used in low to medium voltage applications, while super-junction MOSFETs are preferred for high-voltage and high-efficiency applications. In conclusion, the super-junction MOSFET showcase, in addition to a higher dopant concentration, multiple benefits as lower a lower RDSon, improved thermal impedance or the possibility to use the die in thinner packages.

Improvements have been made not only to the structure but also in the mechanical performance using a different top passivation. The top of the structure is subjected to electrical and mechanical stress. The passivation process is responsible for protecting the active structure from mechanical stress, ensuring it remains isolated. In the past, a simple Nitride layer was used for this purpose, but the interactions with the metallization layer generated some mechanical stress, leading to die cracks. A solution to reduce this impact was the use of an additional layer made with TEOS (Tetraethyl Orthosilicate). Today, the latest super-junction structures complete the top of the die with an extra layer of polyimide.

The better performances, both in conduction and dynamic commutations of the latest super-junction structure, enable the achievement of high efficiency, saving energy, and maximizing power conversion. For example, as shown in Figure 5, the latest super-junction technology can generate an improvement

Figure 3. High Voltage Silicon MOSFET technology evolution



➤ Figure 4. From planar to super-junction structure.

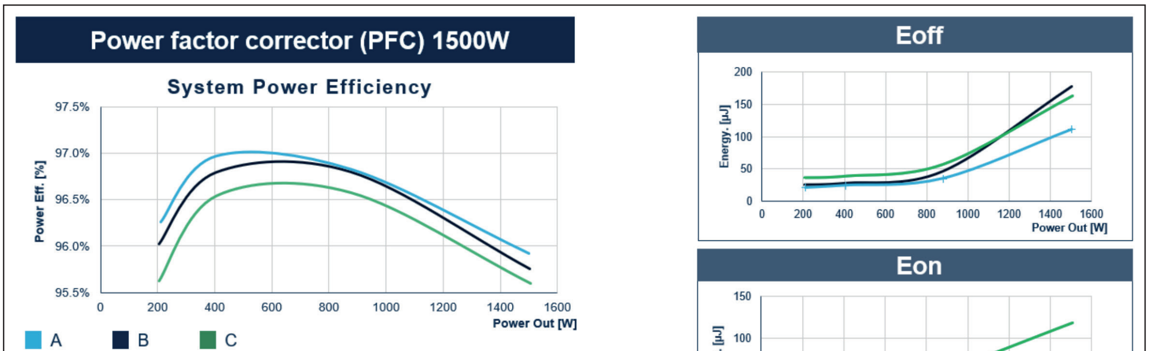
of 0.5%. Although this improvement may initially seem negligible, it is significant when the power level is high. In fact, saving 0.5% in a 10W power system means only 50mW, but the same ratio becomes more significant when we refer to systems that manage kilowatts (kW), like solar converters or automotive power converters.

To complete this overview, it is fundamental to take a look to the Insulated Gate Bipolar Transistor (IGBT), a semiconductor device that is widely used in power electronics. It combines the simple gate drive characteristics of a Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) with the high-current and low-saturation-voltage capability of a bipolar transistor. The IGBT is designed to handle large power levels and is commonly used in applications such as variable-frequency drives (VFDs), electric cars, trains, variable-speed refrigerators, air-conditioners, and even in the power grids for switching or adjusting reactive power. Below a short overview of the different IGBTs topologies is made to show the main differences between them.

Non-Punch-through is the first IGBT technology and has higher saturation voltage VCEsat, slower turn-off speeds and a positive temperature coefficient, meaning that as the temperature increases, the on-state voltage also increases. Punch-through (PT) IGBTs, conversely, can also exhibit a positive temperature coefficient at higher current levels, which can be advantageous for parallel operation, as it helps to prevent thermal runaway. The buffer layer in PT IGBTs indeed reduces the minority carrier lifetime, which results in faster turn-off speeds and lower switching energy.

The Trench PT presents a different structure because it has a vertical inversion channel of the p-type emitter region (while in the previous planar topologies is horizontal), which means that the JFET effect present in planar gate IGBTs (which limits current flow) can now be reduced. By having a vertical channel, the trench gate IGBT enhances conductance modulation efficiency near the emitter region due to the high electron injection, which improves the device's overall performance.

The Trench Field-stop (FS) IGBT is a type of IGBT that combines the benefits of the trench gate structure with those of the buffer layer. This design aims to provide faster switching speeds and lower on-state voltage drops compared to conventional IGBTs. The Field-stop (or buffer) layer is a highly doped n-type region located just below the n- drift



Device	BVdss [V] @ 1mA	Vth [V] @ 250uA	$R_{DSon\ Max}$ [mΩ]*	Qg [nC]
A	650	3.7	45	80
B	600	4	41	106
C	650	4	45	143

➤ Figure 5. Application test and analysis of different devices, comparing main parameters

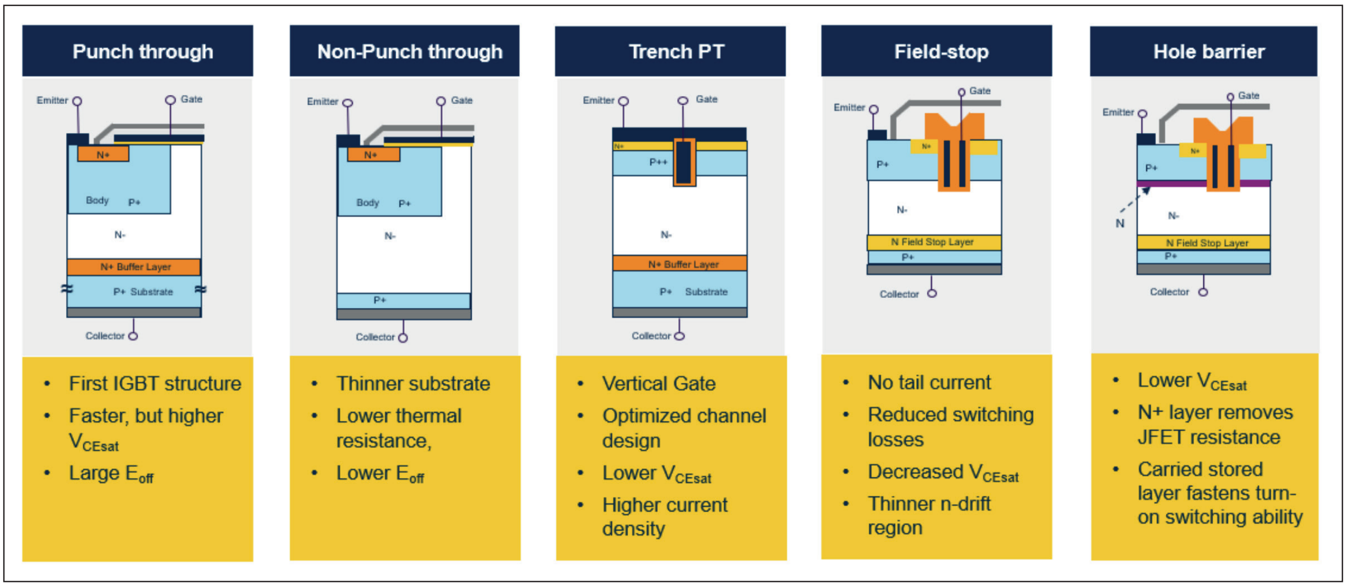


Figure 6. IGBT technology

region. It is designed to stop the electric field from extending into the thick n- buffer layer, which allows for a thinner drift region without compromising breakdown voltage.

The Hole barrier (HB) IGBT is basically a Trench FS which also comprises an additional n-layer to increase the conductivity in the upper-layer zones. This provides a higher VCEsat, improving the turn-off behavior and reducing the tail currents. By managing the movement of electrons within the device, Hole barrier IGBT can achieve faster switching speeds and lower losses, making them suitable for applications where efficiency is critical.

The ability to withstand hard stress, such as a short circuit, is a critical feature for many applications, particularly in power electronics where unexpected short circuits can occur for various reasons, such as rotor blockage or component failure. To address this requirement, different strategies are implemented into the IGBT structure. One such strategy is the generation of dummy cells. These cells do not participate in the conduction of the structure, allowing it to sustain higher short circuit current values. The trade-off is a lower saturation current and lower current density. This strategy balances the need for short circuit robustness with the impact on performance.

The term “narrow mesa” in the context of Trench Field Stop (FS) IGBTs refers to the design of the area between the trenches where the gate oxide and field stop layer are located.

In a Trench FS IGBT, the gate electrode is embedded in narrow trenches etched into the silicon. The space between these trenches is known as the mesa. A narrow mesa means that the distance between the trenches is minimized. This design allows for a higher cell density, which can increase the current-carrying capability of the device and reduce on-state resistance (RDSon). The Field-stop layer is optimized to prevent the electric field from extending too deeply into the device, which helps to maintain a high breakdown voltage with a thinner drift region.

The narrow mesa design is part of the overall structure that contributes to the improved

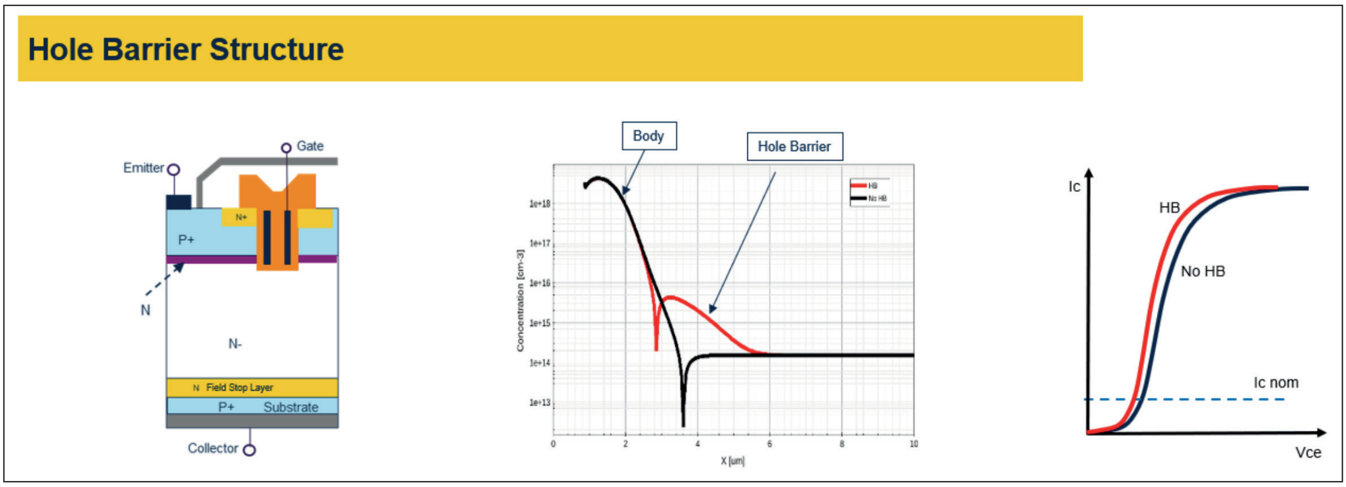
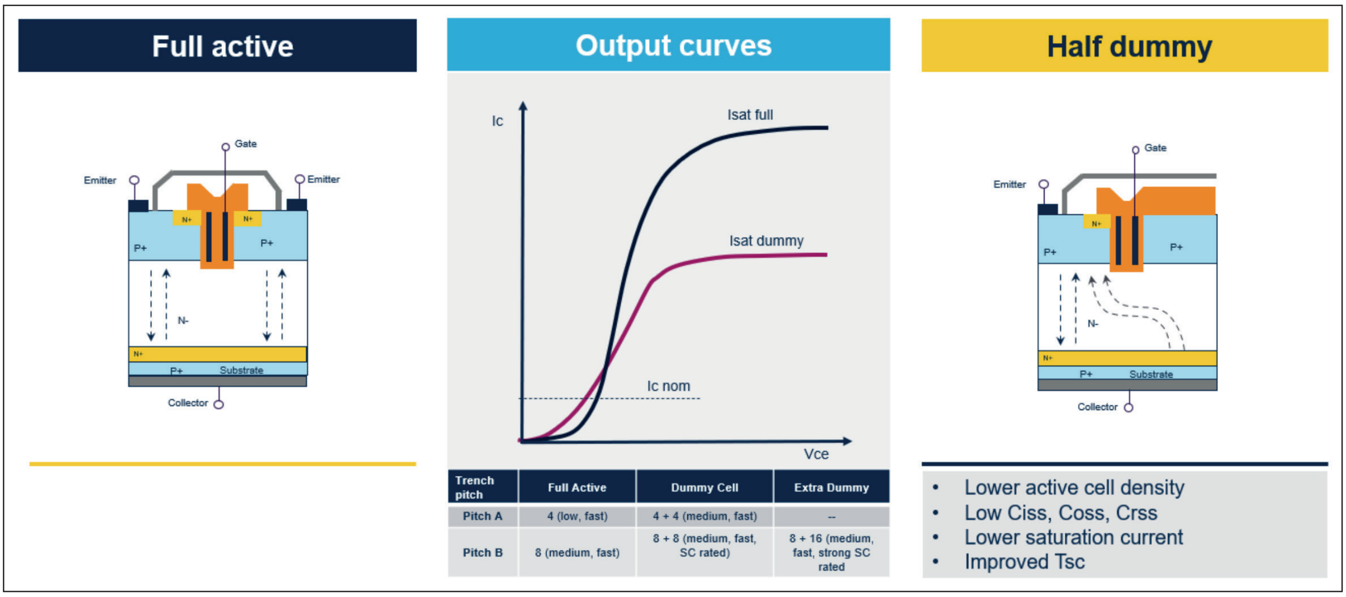


Figure 7. The Hole barrier structure



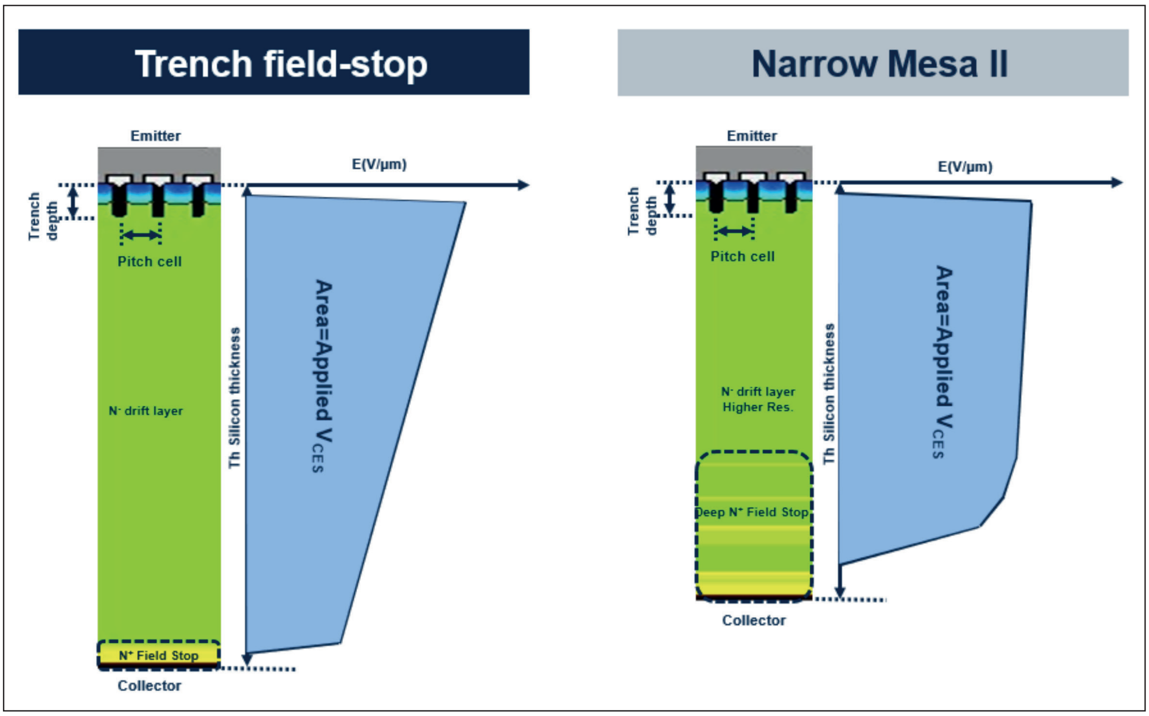
Trench pitch	Full Active	Dummy Cell	Extra Dummy
Pitch A	4 (low, fast)	4 + 4 (medium, fast)	--
Pitch B	8 (medium, fast)	8 + 8 (medium, fast, SC rated)	8 + 16 (medium, fast, strong SC rated

➤ Figure 8. Trench layout strategy

performance of Trench FS IGBTs, offering benefits such as lower conduction losses and faster switching speeds compared to traditional planar IGBTs. When referring to "Narrow Mesa II" or "Generation II" in the context of IGBTs, it likely indicates an evolution of the trench IGBT technology where the narrow mesa concept has been further refined or optimized.

Manufacturers often release different generations of IGBTs with improvements in the cell design, trench technology, and other features to achieve better performance. In terms of advantages, Generation II Trench IGBTs over Narrow Mesa showcases lower on-state resistance, and faster switching characteristics lead to higher efficiency in power conversion applications. They also possess the ability to handle higher currents in a smaller area makes these devices suitable for compact designs. Finally, improved efficiency results in less heat generation, which can simplify thermal management requirements. Power electronics has seen significant advancements over the last years, driven by the need for more efficient, compact, and reliable power conversion systems, and their evolution will likely be determined by the specific requirements in the considered application.

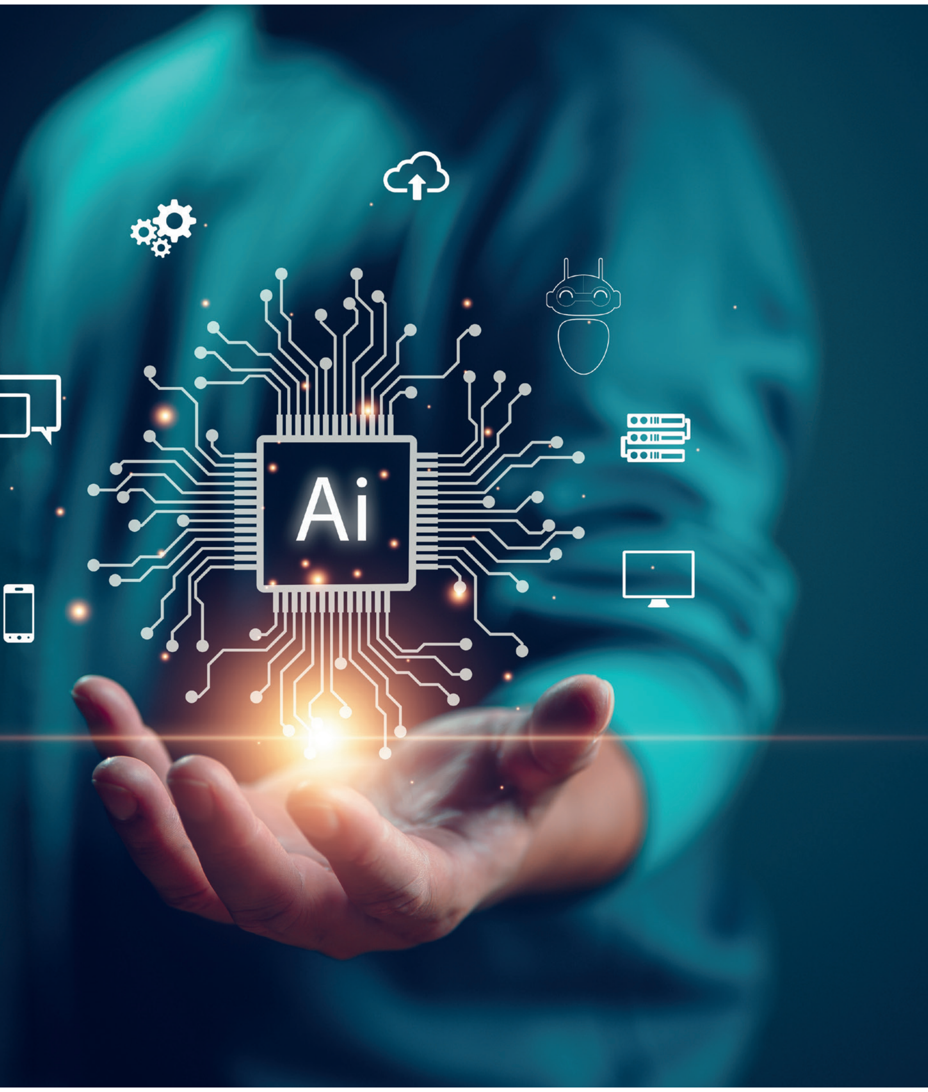
Integration and hybrid approaches may also emerge, where silicon is used alongside wide-bandgap materials to optimize performance and cost. Additionally, advancements in silicon technology may extend its viability in certain high-performance areas.



➤ Figure 9. Improvement from Trench Field-stop to Narrow Mesa II

Embedded excellence

For the 20th time, outstanding innovations from the field of embedded system technologies have been honoured with the embedded award at the embedded world Exhibition & Conference. "It is fascinating to see how innovations are being successfully driven forward across all disciplines in the embedded systems world", emphasised jury chairman Prof. Axel Sikora. There were eight category winners – here we focus on those with a power electronics relevance.



Artificial Intelligence - Voltai

"Read the Freaking manual" – this is a term every engineer in the electronics industry is familiar with. Engineers today are swimming in an ocean of documents. An average microcontroller has 10,000 – 50,000 pages of documents.

This is just one chip, an engineer should integrate multiple of these chips to build a system – just 10x the documents they need to handle. Let alone the fact that these documents are written and read by non-native English speakers riddled with mistakes. On the other hand, semiconductor companies have to hire hundreds of support engineers (FAEs) to support their customers.

Even with this, they can only support the top 5-10% of their customer base. Semiconductor companies are losing business and unable to support their long tail customers. If an engineer reaches out for support, they would need hours if not days to respond to an answer which is mostly along the lines of "Read the user manual".

The entire hardware industry's development speed is capped by how fast the engineers can read thousands of pages of PDFs. This is the sad state of our industry. This is the problem we're after! We have built foundation models like GPT specialized on electronics and semiconductors.

Our models cannot write poetry Models trained for hard-core engineering tasks, not for writing emails or poems. Our models today can, Help engineers answer questions they have about a chip – no more scrolling thousands of pages Write firmware code Help select the best part for their project Point out errors and help debug their firmware We support multiple languages, show sources for every answer we product, have 0 hallucinations.

Our model ingests a wide range of resources, including user manuals, architecture manuals, datasheets, errata sheets, forum discussions, internal databases and code samples, circuit diagrams, etc. Through extensive training on this data, we create an AI model proficient in electronics and well-versed in the intricacies of specific chips. Started less than 2 years ago, Voltai is answering questions of engineers behind the hood at some of the top semiconductor companies of the world.

Hardware - Apollo510 MCU - Ambiq

AI has been restricted to the Cloud as it requires huge volumes of data, compute, and performance for its intensive calculations. There are tremendous benefits in offering AI on devices for consumers to use 24/7, such as gaining insights into their health via their smartwatches or asking their virtual assistants on smart speakers for help. Factories and agriculture industries can leverage smart devices like motion detectors and location trackers to help drive efficiency and productivity.

How to enable AI on everything and everywhere has been Ambiq's mission for the last 14 years. In a highly competitive semiconductor industry, Ambiq has carved out a unique existence in delivering truly ultra-low power microprocessors with unprecedented energy efficiency and compute performance that drive the latest endpoint devices, including digital health devices, factory automation, agriculture, smart homes, and 75% of the global wearable products.

Reducing cloud dependence has four major benefits for AI on endpoint devices: power savings, privacy protection, latency reduction, and increased robustness. These benefits offer immense value for manufacturers and consumers, and the debut of Ambiq's Apollo510 MCU is set to further this vision of enabling intelligent devices everywhere.

Ambiq's Apollo510 MCU was purpose-built to create more capable endpoint devices that enable AI. The Apollo510 uses subthreshold technology to perform AI at lower power consumption levels than previously thought possible. This incredible reduction in power consumption allows endpoint device manufacturers to dramatically expand their devices capabilities, reducing dependence on the cloud. They can add intensive and complex features such as AI that sips power versus drains.

The Apollo510 upgrades its hardware from previous generations furthering its energy optimization per compute cycle. It uses the Arm-Cortex M55 with Helium to achieve better latency and power consumption. For perspective, an AI benchmark test demonstrated 22X better efficiency than the already best-in-class Ambiq Apollo4, and a nearly 300x improvement over typical Cortex-M4 devices. This makes the Apollo510 the most energy efficient use case for the Arm-Cortex M55 on the planet. This combination of performance and efficiency will allow our customers to deploy sophisticated speech, vision, health, and industrial AI models on battery-powered devices everywhere, marking the start of the age of truly ubiquitous, practical and useful AI.

SoC/IP/IC Design - MAX40109 pressure sensor system on chip with single flow calibration: analog devices

Today's industrial pressure sensors use a resistive Wheatstone bridge that produces a small differential voltage which is prone to non-linear output caused by temperature and pressure variation. Existing solutions require a two-pass calibration to correct for this non-linearity. In the first pass, the pressure sensor manufacturers use an expensive laser trimming process to remove the unwanted common-mode offset. This adds a complex manufacturing step to the calibration process.

The second pass then implements linearization and temperature compensation. The MAX40109 is a low-power, precision sensor interface SoC that revolutionizes this process through a single pass calibration reducing overall system complexity and calibration costs.

Single flow calibration reduces one-time factory calibration and test time by more than 30%. This process also removes up to 10 laser trim resistors from the existing system solution. Another design challenge is the overall solution size.

Discrete components such as amplifiers, ADC, DAC and DSP blocks are used alongside PTC for temperature measurement. This leads to larger solution size, higher system cost and longer time to market. MAX40109 is a high-precision, programmable SoC, with integrated ADC, MTP, DSP and a DAC. MAX40109 enables integrated temperature measurement directly from the bridge, removing the need for external thermistors. This reduces overall solution size by more than 70%.

The MAX40109 simplifies the system design with the innovative features such as analog zero-pressure offset compensation up to ±93 mV/V and temperature measurement directly at the bridge. This reduces design complexity and system cost by removing the tedious laser-trimming process and reducing an external temperature sensor. The SoC also comes integrated with a DSP engine for 3rd order polynomial calculation which is a key block that generates the calibrated output, eliminating the need for an additional processor.

Another innovative aspect of MAX40109 is the combination of various digital and analog output schemes including Digital 1-wire, PLC and I2C interfaces, and Analog voltage (0 – 5V) as well as the current (4 – 20mA) output loop. The low-power operation, analog outputs and high voltage industrial Power-rail operation makes it directly compatible to work with Industrial systems.

The community choice award - ST87M01 - STMicroelectronics

This project within our company was designed solely in Europe. The module itself and all internal integrated circuits are entirely designed and

produced by ST in Europe only, which ensures control and management on the complete supply chain. This represents a unique offering on the market in terms of quality, safety and longevity of the products. It gives our customers a major advantage especially in the Metering market (water, gas, electricity meters).

The STM8701 offers flexibility for product developers, presenting a fully programmable IoT platform that lets users embed their own code directly in the module for simple applications. Alternatively, the module can be combined with a separate host microcontroller, permitting many more sophisticated use cases. The ST87M01 combines ST's know-how, including microcontrollers, AI solutions, sensors, actuators, PMUs, converters, interfaces, memories to enable next-generation IoT ecosystems. Bringing together reliable geolocation capability with long-term assured cellular connectivity, the ST87M01 module addresses emerging massive IoT applications such as smart traffic-emergency lights, to become mandatory in Spain by 2026. The new lights supersede the passive emergency triangle, by providing real-time car geolocation to the local traffic-control system in the event of accident, consistent with the European road safety charter.

STMicroelectronics' ST87M01 ultra-compact and low-power modules combine highly reliable and robust NB-IoT data communication with accurate and resilient GNSS geo-location capability for IoT devices and assets. The fully programmable, certified LTE Cat NB2 NB-IoT industrial modules cover worldwide cellular frequency bands and integrate advanced security features.

The ST87M01 provides extended multi-regional LTE coverage. The integrated native GNSS receiver with multi-constellation access ensures enhanced and highly accurate localization along with optimized power savings features. The ST87M01 provides with ultra-low power consumption — less than 2µA in low-power mode — and transmit output power up to +23dBm, the ST87M01 targets wide-ranging IoT applications that require ultra-reliable Low Power Wide Area Network (LPWAN) connectivity. These include smart metering, smart grid, smart building, smart city and smart infrastructure applications, as well as industrial condition monitoring and factory automation, smart agriculture and environmental monitoring.

The modules also integrate a state-of-the-art ST4SIM embedded SIM (eSIM), certified according to the latest industry standards, such as the recent GSMA eSA (Security Assurance) certification, that further enhances asset miniaturization and security. There is also a state-of-the-art embedded secure element (eSE).

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ESDA Electronic System Design Alliance

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FOA Fab Owners Alliance

MEMS & SENSORS INDUSTRY GROUP®

SOI Industry Consortium

Boosting performance with the merged *p-i-n* SiC Schottky diode

Delivering greater reliability at high efficiency, the merged *p-i-n* SiC Schottky diode combines a low forward voltage with high surge-current capability

BY LLEW VAUGHAN-EDMUNDS FROM NAVITAS SEMICONDUCTOR

THE WIDE-BANDGAP REVOLUTION in power conversion is well under way. To fulfil efficiency and power density targets in energy-conscious applications, designers are now rejecting silicon devices in favour of alternatives delivering superior performance.

Offering the greatest commercially maturity within the wide bandgap fraternity is SiC. Producers of this class of semiconductor have now released several generations of diodes and power MOSFETs, each offering successively improved performance. Sales of these devices have soared in recent times to hit nearly $3 billion last year, and growth is forecast to continue at around 40 percent per year as deployment expands into evermore applications.

SiC devices outperform their silicon counterparts in both conduction and switching characteristics. First to market within this family of power devices is the SiC Schottky barrier diode. Compared with the silicon fast-recovery diode, it has a lower forward voltage and a superior reverse recovery. One upshot of these strengths is a tremendous reduction in overall energy losses. Yet another merit of the SiC

Schottky barrier diode is a stable reverse-recovery time over the full operating temperature range. In comparison, the silicon fast-recovery diode is impaired by an lengthening recovery time at higher temperatures.

However, the SiC Schottky barrier diode is far from perfect. All Schottky diodes, regardless of material system, are inherently vulnerable to current surges. This is a known hazard in power-factor correction circuits, used in power supplies for converters and inverter systems.

One option for addressing this issue is to turn to *p-i-n* diodes, which offer greater reliability in such situations. However, reliability is traded for reduced efficiency, due to a higher forward voltage. It's not a great compromise, as a lower energy efficiency is undesirable. In equipment such as server power supplies, a diminished efficiency leads to a higher electricity bill, increased cooling management and a slower return on investment.

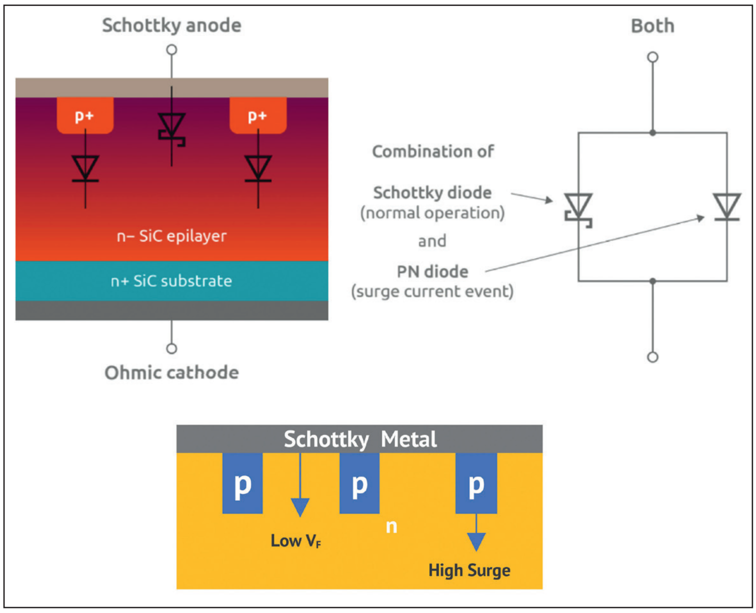
A compelling solution is the merged *p-i-n* SiC Schottky (MPS) diode. This device marries the best features of Schottky and *p-i-n* diodes in a single device by combining the surge-current robustness and low reverse leakage of the *p-i-n* diode with the low forward voltage of the Schottky structure. Equipped with a superior breakdown voltage, excellent reverse-recovery characteristics, stability over temperature, and the high-temperature operating capability associated with all SiC devices, the MPS diodes that have been introduced in power factor correction and boost circuits are enhancing reliability and significantly increasing the overall efficiency of the power-conversion system.

Design and optimisation

A key difference between a conventional Schottky part of the device structure and the MPS diode is that the latter contains additional *p*-doped wells, implanted in the drift zone. These wells form a *p*-ohmic contact with the metal at the Schottky anode, while also creating a *p-n* junction with the SiC drift layer. The result is effectively the combination of a Schottky diode and a *p-i-n* diode, connected in parallel (see Figure 1).

With this design, in normal operation the Schottky carries almost the entire current. On the other hand, during high-current surges, the voltage across the MPS device rises, causing conduction in the drift layer of the *p-i-n* diode. As this intrinsic diode has a lower resistance than the Schottky, current is diverted, reducing dissipation and relieving thermal stress.

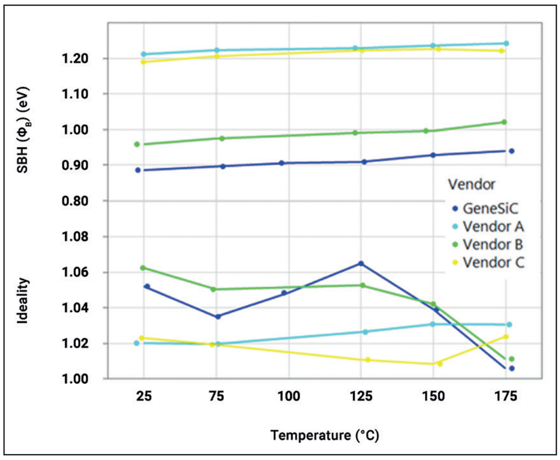
When the MPS diode operates under reverse bias, the maximum field strength occurs across its drift region. This contrasts with the situation in a standard Schottky architecture, where the greatest field strength occurs at the metal barrier. A downside of the Schottky diode is that imperfections in the barrier allow a relatively large leakage current to flow. That's not the case with the MPS diode, which benefits from moving the maximum field strength away from the metal barrier. This design ensures that the leakage is lower than that of a standard SiC Schottky diode.



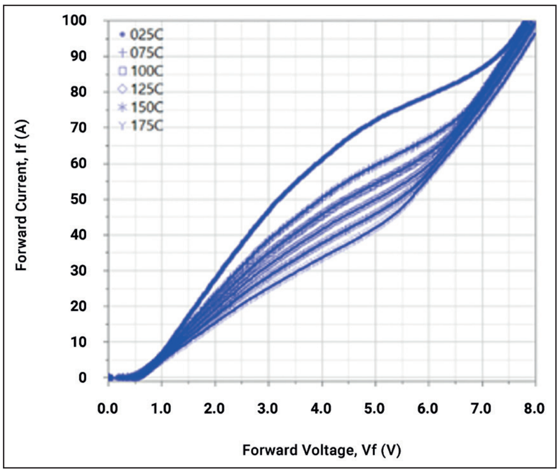
➤ Figure 1. MPS diodes combine *p-i-n* and Schottky diode attributes.

By optimising the dimensions and doping of the *p*-type wells, device designers can engineer the forward voltage drop, surge-current capability and leakage current of the MPS diode to meet specific requirements. Additional improvement comes from thinning the substrate below the drift region. This trims the MPS forward voltage and the thermal resistance between the Schottky area and back-side metallisation, leading to lower energy losses, enhanced thermal efficiency and greater reliability.

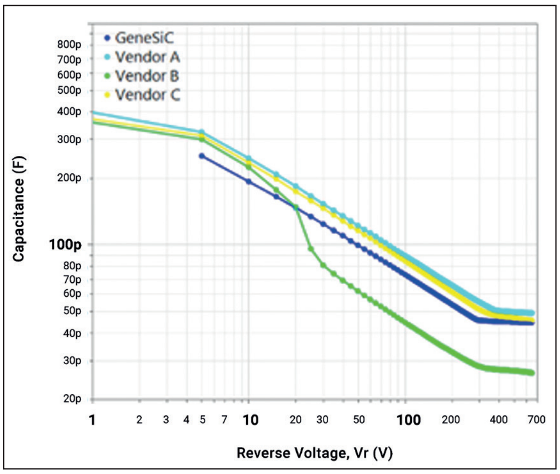
At Navitas, we have an enviable track record in developing and producing SiC MPS diodes. Now in their fifth generation, our 650 V SiC MPS diodes feature a high surge-current capability and a low forward voltage to minimise losses in the forward-biased mode. Our devices also offer an extremely low reverse-leakage current and high avalanche



➤ Figure 2. Low-current, forward current-voltage (I-V) characteristics for 10 A SiC MPS diode.



➤ Figure 3. High-current, forward current-voltage (I-V) characteristics from 25 °C to 175 °C.



➤ Figure 4. Capacitance-voltage (C-V) curves for Navitas and competitor SiC MPS diodes.

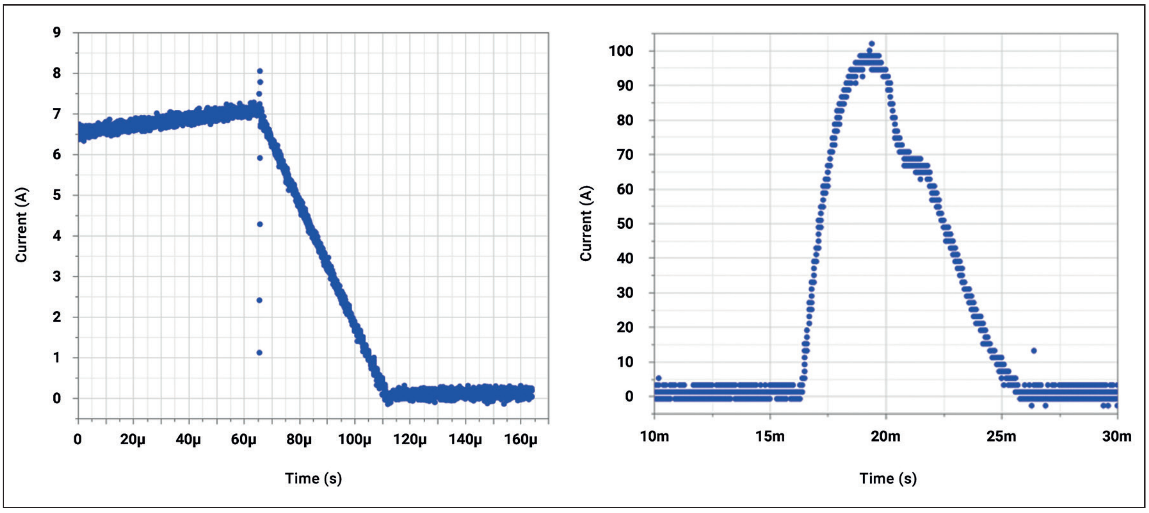
robustness. It is a combination of attributes that comes from optimising the device architecture and engineering the barrier metallurgy to ensure an ultra-low Schottky barrier height of just 0.88 eV at 25 °C.

One of the downsides of typical Schottky and MPS diodes, which feature a titanium metal barrier, is a trade-off between the Schottky barrier height and the reverse leakage current. Thanks to our novel, proprietary barrier metal, our MPS SiC diodes have a Schottky barrier height that's more than 26 percent lower than alternative titanium-barrier devices, and a leakage current of just 100 nA – that is at least six times lower than the norm. In addition, our devices offer enhanced shielding of the Schottky metal interface, minimising any increase in reverse leakage current at higher voltages.

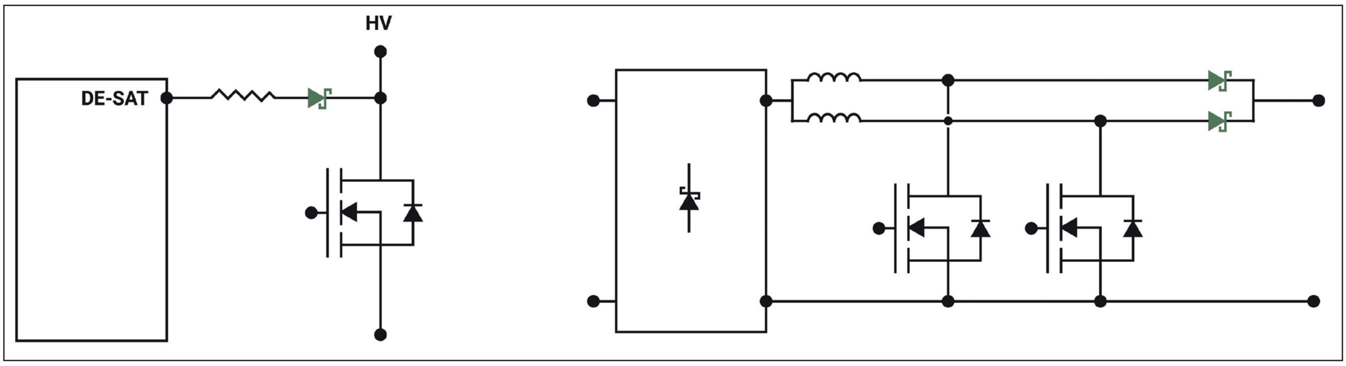
We have measured the forward current-voltage characteristics of these diodes at low currents and at temperatures from 25 °C to 175 °C (see Figure 2). These results reveal consistent linearity across this wide temperature range, indicating a stable Schottky barrier height, indicative of a good spatial homogeneity of the Schottky metal interface.

There is a small increase in the Schottky barrier height. That's a common tendency amongst MPS diodes from various vendors. One way to evaluate this increase is to consider 'ideality', a measure of how closely the diode's behaviour conforms to the ideal diode equation under different conditions. Ideality typically decreases with temperature, and has a value that's close to 1 in well-behaved diodes under normal conditions. If there are deviations from this value, they tend to come from unwanted effects, such as recombination currents and parasitic series resistances. Note that real-world diodes can depart from ideal behaviour, and often display an ideality greater than 1.

We have also recorded the current-voltage characteristics of our MPS diodes at higher currents (see Figure 3). These plots, taken at various



➤ Figure 5. (a) Avalanche testing and (b) surge current characteristics of Navitas MPD diodes.



➤ Figure 6. Navitas MPS diodes in a desaturation detection circuit and an interleaved power-factor correction (PFC) circuit.

temperatures, show that there is a cross-over from unipolar (SiC Schottky) to bipolar (*p-i-n*) operation at about 90 A at 25 °C. This cross-over decreases to 50 A at 150 °C. Our plots also show a lowering of the knee-voltage at higher temperatures, which helps maintain a low temperature co-efficient of the on-state voltage drop at the rated current of 10 A.

To benchmark our devices, we have compared the capacitance-voltage curves of our diodes with those of rival products. These plots reveal that our MPS diode has one of the lowest values of capacitance charge, which ensures low reverse-recovery losses.

The low capacitance charge also enables our MPS diodes to have a good value for the common figure-of-merit for this device, defined as the product of capacitance charge and forward voltage. While improvement on one of these fronts tends to be detrimental to the other, a good figure of merit balances a low forward-voltage drop, key to trimming power losses, with a low capacitance charge that ensures superior switching performance. Attaining the lowest possible value for each helps to enhance the overall diode performance in power electronics applications.

Another important characteristic for the MPS diode is its level of avalanche robustness. We assess this with unclamped inductive switching tests. Values for the current waveform under unclamped inductive switching and current-surge conditions reveal a high value for the non-repetitive surge current, confirming our diode's robustness (see Figure 5).

Made for TV

Our MPS diodes can make a positive contribution to a number of applications. They offer a superior performance in: boost circuits, which raise the solar-panel output voltage to the 450-600 V required for the inverter; and in power-factor correction circuits, which are mandatory in line-powered applications above 75 W, according to IEC/EN 61000-3-2. Power-factor correction circuits are used in power supplies for telecom equipment, for data centre servers and for lighting systems.

SiC MPS diodes can also deliver benefits in consumer devices, such as televisions. With the advent of 4K UHD, the latest displays are demanding significantly more power than their predecessors, leading to a greater emphasis on efficiency, for both realising a suitable energy rating and for maintaining proper performance. As well as satisfying this requirement, efficient power supplies usually improve the performance of the display. Often the power supply is positioned directly behind the display, and if it generates too much heat due to a low efficiency, this impairs colour rendition.

We offer our SiC MPS diodes in various package options, which can deliver several advantages in different applications. For high-voltage sensing circuits, like desaturation detectors for overcurrent protection, as well as in the gate-drive bootstrap circuits of high-side switches (see Figure 6), the DO-214 and TO-252-2 packages are ideal solutions.

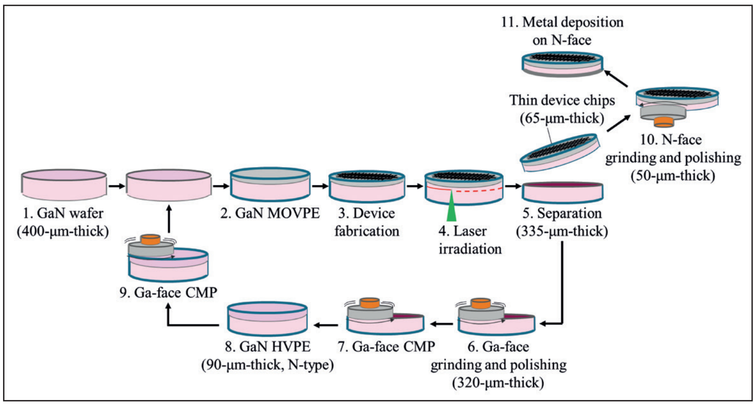
On the other hand, the TO-247-3 package provides extra flexibility when high-power density is required, and can help reduce the bill of materials in applications like interleaved PFC circuits, which share a common cathode between two diodes. The key point is that SiC MPS diodes are compelling direct replacements for Schottky diodes in circuits that need to combine a high energy efficiency with robustness and reliability when exposed to surge currents. Such conditions occur when powering highly capacitive or inductive loads, or when the power quality of the main AC line is poor. As a straightforward drop-in replacement, our devices are easy to design-in for a significant boost in power-conversion efficiency.

Cutting the cost of vertical MOSFETs with laser slicing

Slicing substrates with a 532 nm laser promises to trim the cost of producing GaN power MOSFETs without compromising performance

GaN VERTICAL MOSFETs are very promising power devices for electric vehicles, having the upper hand over SiC equivalents in channel mobility, a key metric. However, commercial success is held back by the high cost of the native substrate.

To address this concern, a number of teams have been investigating technologies for recycling GaN substrates. They include a collaboration between researchers at Mirise Technologies, Nagoya University and Hamatsu, that is claiming to have produced the most comprehensive demonstration of success with this approach.



➤ The GaN recycling process involves laser slicing and HVPE growth of GaN to maintain the thickness of the substrate.

According to team spokesman Takashi Ishida from Mirise, previous reports of recycling GaN substrates have been limited to evaluating just part of the process. "It is indispensable to evaluate the device characteristics fabricated on a recycled wafer," argues Ishida, "and our paper reported this result for the first time."

Ishida adds that while their result is encouraging, there's more work to do before their process can be applied on an industrial scale. As GaN substrates need to be recycled multiple times to drive down manufacturing costs, there is a need to prove that devices are not compromised when grown on substrates produced from several rounds of recycling.

The Japanese partnership's recycling process, outlined in the figure, involves separating the device and substrate with a 532 nm laser. This source, irradiated onto the substrate from the N-face, drives decomposition into metallic gallium and nitrogen via two-photon absorption at the focal plane.

Following separation, the N-face of the chips are ground and polished to obtain smooth surfaces, prior to metal deposition and mounting into packages.

Grounding and polishing is also applied to the Ga-face of the released substrate, prior to chemical mechanical polishing to realise flatness at the atomic level, followed by HVPE, used to deposit a layer of GaN with a thickness of around 90 µm. According to the team, after an additional chemical mechanical polishing step, the GaN substrate is as good as new.

To assess their process, the team have measured lateral MOSFETs and vertical *p-n* diodes fabricated from the same wafer. Both classes of device have been formed from epiwafers produced during the MOCVD of: a 4 µm-thick *n*-type GaN layer, doped to 1 x 10^{17} cm^{-3}; followed by a 2 µm-thick *p*-type GaN layer, doped to 5 x 10^{17} cm^{-3}.

This study began by evaluating the performance of both classes of device before and after slicing from a GaN substrate. Plots of the MOSFET drain and gate current at various gate voltages, and diode reverse currents under different values of reverse bias, showed no apparent changes due to laser slicing. This led the team to conclude that the devices are 'virtually unaffected' by the slicing process, which can lead to heating from the laser source and stress associated with the separation step.

Ishida and co-workers have compared these measurements with those for lateral MOSFETs and vertical *p-n* diodes produced using a recycled substrate. Results are very similar, with the difference in gate leakage of the lateral MOSFET attributed to a variation in the quality of the gate insulator.

According to the team, their results show that there is no critical degradation in device performance after the GaN recycling process.

Ishida says that in addition to recycling the GaN substrate, there needs to be an increase in its size to make the cost of device production more competitive. The team are interested in demonstrating their re-cycling process with larger GaN substrates.

REFERENCE

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Dealing with dynamic change and technological innovation

A Q&A with leading global independent electronic components distributor, **WIN SOURCE,** providing valuable insights into how the company responds to the challenges and opportunities facing the power electronics industry into the future.

PEW: *Please can we start with a brief background on the company – some history, key milestones – the journey from launch to where it is today?*

WS: Established in 1999, WIN SOURCE is a leading global independent distributor of electronic components with over 24 years of experience. The company began its journey in the electronics distribution field by opening its first retail and offline stores in Shenzhen, China. Over the years, WIN SOURCE has grown significantly, and in 2006, it began providing comprehensive supply chain services to local Fortune 500 companies. In 2015, to address the information asymmetry in electronic component procurement, WIN SOURCE launched Asia's first overseas B2B e-commerce platform, WIN SOURCE Online Store (https://www.win-source.net/), dedicated to optimizing the electronics industry's procurement chain. Following this, the company extensively expanded its international business department, establishing localized global business units to meet the growing needs of overseas markets. In 2021, the company achieved sales of $389 million, demonstrating rapid business growth and high market acceptance. By 2022, it ranked second among Asia's top ten electronic component distributors as rated by SourceToday, with sales exceeding $613 million. In the most recent year of 2023, WIN SOURCE placed 18th in the global top 50 electronic component distributors list, further solidifying its leading position in the industry.

While continuing to expand its operations, WIN SOURCE also focuses on strengthening industry collaborations and has become an active member of several key industry associations, including ERAI and IPC, etc.. This strategy not only helps the company stay in sync with developments in the electronic components industry but also further consolidates its market leadership. Additionally, WIN SOURCE has obtained several high-standard international certifications, including ISO 9001 and ISO 14001, which attest to the quality of its products and services meeting international standards. Through continuous innovation in supply chain management technology and expansion of the global supply chain, the company has successfully opened doors to emerging markets and significantly enhanced its service capabilities in existing markets. Currently, the company has offices in multiple countries, including the USA, Germany, and Mexico, and plans to further expand its international footprint this year.

The journey of WIN SOURCE is filled with achievements, and the company remains committed to providing exceptional products and supply chain services to its customers, growing together with them, and advancing the development of the electronic components industry.

PEW: *In terms of your product range, which covers a wide spectrum of components, including integrated* *circuits, discrete semiconductors, circuit protection, optoelectronics, sensors and transducers, connectors/interconnects, capacitors, and more. How do you ensure that the parts you procure are genuine?*

WS: First of all, we have implemented a continuous maintenance quality management system to ensure effectiveness and drive process improvements. Our system complies with multiple industry standards, including AS9120B, ISO 9001:2008, ISO13485, ISO28000, ESD-S20.20, and IDEA-STD-1010-B.

Furthermore, we maintain a dedicated quality management team. This team conducts regular assessments to evaluate the ongoing suitability of WIN SOURCE's quality system through internal audits and comprehensive quality reports. These assessments are based on audit findings, customer feedback, process performance, product compliance, and the status of preventive and corrective actions, as well as previous management reviews.

Integral to our commitment to quality assurance is our in-house inspection capability. Every component undergoes a meticulous inspection and is verified for its source by WIN SOURCE's quality testing department. We employ advanced methods, such as 200x magnification, solderability testing, acetone verification testing, and more, before these components enter our inventory and are dispatched to end customers.

Additionally, we have developed WIN SOURCE's unique quality control system, which includes packaging inspections, shipping label checks, visual product inspections, non-destructive testing, and strict adherence to precise environmental and humidity control. This compliance extends to our ANSI/ESD S20.20 handling processes, ensuring operational precision and efficiency.

Lastly, we place significant emphasis on supplier qualification control. Recognizing that the source of components directly impacts part quality, we consistently adhere to the ISO 9001:2008 management system. We maintain rigorous standards when selecting supplier partners, collaborating exclusively with high-standard distributors who meet our stringent supplier criteria. These partners include manufacturers, authorized distributor-resellers, OEMs, CMs, and reputable independent distributors. These partnerships reinforce the integrity of our robust supply chain.

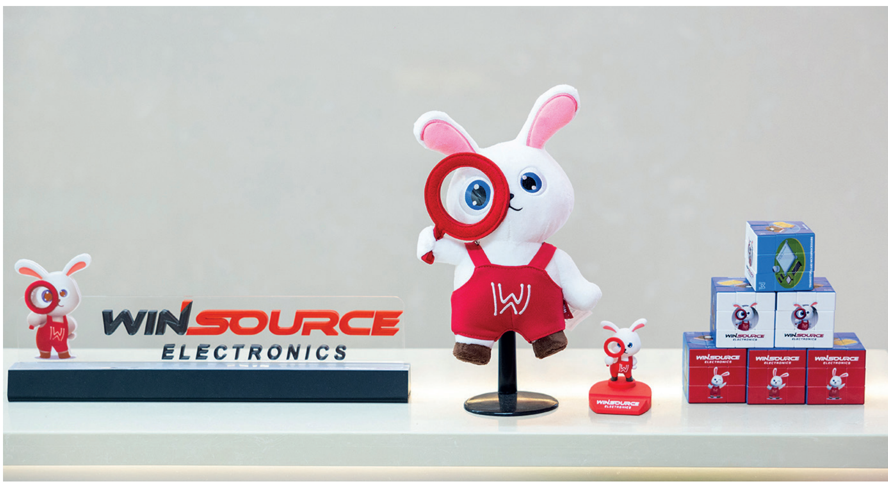
We understand that product quality assurance is paramount because customer trust is our most valuable asset. We hope our customers can purchase WIN SOURCE products with 100% confidence. It's not just about sourcing suppliers from Asia who can offer competitive prices and advantages; it's about finding a partner that provides a comprehensive range of products, specializing in obsolete and hard-to-find component procurement, competitive pricing, and highly reliable quality to genuinely maintain the stability of our customers' supply chains. This enables them to focus more on production research and development.

Our goal is to establish long-term partnerships, grow together with our customers, and provide enduring value to them. Therefore, choosing Win Source means selecting a trustworthy partner with diversified product offerings, competitive prices, and outstanding quality assurance, allowing you to concentrate on your core business with peace of mind.

PEW: *You also promote yourselves as very much a solution provider, focusing on topics such as global sourcing, obsolescence management, cost control management, shortage control management, alternatives, and excess inventory management. Can you say a little bit about each in terms of the ways in which you can help end users address these issues?*

WS: WIN SOURCE is committed to assisting clients navigate a variety of industry challenges with comprehensive solutions. By leveraging our strengths, we are able to provide efficient and reliable support to our customers.

Firstly, we hold a significant advantage in global sourcing. By continually optimizing our supply chain systems and expanding global procurement channels, WIN SOURCE has established an extensive international supply network. We currently offer around 1.12 million SKUs of electronic components from over 3000 manufacturers, ensuring that we can provide the most comprehensive and high-quality products to our customers. Secondly, with our proprietary big data IT services platform, we continually enhance our online shopping platforms and supplier networks. We have also developed an in-house supply chain operation system that includes subsystems for sales, purchasing, warehousing, logistics, and marketing to support our global supply chain. This enables our customers to achieve intelligent BOM procurement,



quickly secure shortage and obsolete inventory, and continuously optimize and reduce procurement and production costs. Additionally, WIN SOURCE's professional team can provide alternative solutions to meet specific customer needs and help them find the best electronic component solutions when facing challenges. We also offer excess inventory buy-back services, solving the problem of inventory overstock for businesses and helping them optimize asset allocation.

By utilizing our global network, robust supply chain management, and unique comprehensive services, we offer a intelligent electronic component procurement solution, helping our clients maintain a competitive edge in a fiercely competitive market environment.

PEW: *More generally, the whole supply chain seems to have some level of ongoing disruption – how do you see your role as a distributor changing to help customers with these issues?*

WS: Amid the instability of the external environment and shifts in the international competitive landscape, global supply chains face ongoing disruptions. As a leader in the electronic components industry, WIN SOURCE recognizes that our role has evolved from a traditional distributor to a partner, enabling us to more effectively help our clients navigate these challenges.

In recent years, WIN SOURCE has focused on strengthening business continuity. We have developed strategic supply chain plans that enhance synchronization across all links of the supply chain, improve visibility and agility, and build resilience. This makes our supply chain more adaptable to geopolitical shifts and natural disasters. Furthermore, we continuously optimize our supply chain systems and expand our global sourcing channels, imposing stricter quality controls during times of change.

Our unique quality control system includes checks on packaging, inspection of cargo labels, visual inspections, and nondestructive testing, adhering to precise environmental and humidity controls, and following processes certified under ANSI/ESD S20.20. This stringent quality control minimizes the risk of our clients purchasing non-standard or inferior products. In summary, regardless of how the focus shifts within the electronics manufacturing industry, our company adapts promptly to meet the actual demands.

WIN SOURCE plays a crucial role in assisting our clients with supply chain challenges. Our profound understanding of the industry and our global influence enable us to anticipate and adapt to changes in industry trends. This helps our clients respond swiftly to the ever-changing market conditions, further enhancing our status as a trusted partner, ensuring that our clients maintain business continuity and competitiveness in the face of global supply chain challenges.

PEW: *Especially when it comes to evolving their procurement and inventory management strategies?*

WS: In formulating procurement and inventory management strategies, supply chain disruptions have become a norm that businesses must seriously consider. Faced with this ever-changing environment, companies need to implement flexible, forward-thinking planning and effective risk management strategies.

We have been undergoing a digital transformation in our business operations, integrating powerful technologies such as artificial intelligence, automation, and the Internet of Things into our business model and organizational changes. This includes the development of intelligent systems to enhance the coordination and transparency of business processes, thereby improving overall operational efficiency and elevating service quality from the ground up. Through our intelligent supply chain system, customers can quickly find

By utilizing our global network, robust supply chain management, and unique comprehensive services, we offer a intelligent electronic component procurement solution, helping our clients maintain a competitive edge in a fiercely competitive market environment

the components they need, whether they are obsolete, EOL or regular parts, all while ensuring cost-effectiveness and quality assurance. These initiatives not only strengthen our capabilities but also contribute to supply chain security, helping to alleviate procurement pressures for our clients. Additionally, we have developed a intelligent online platform, WIN SOURCE Online Store (https://www.win-source.net/), which integrates global supply chain data, enabling our customers to resolve their procurement needs in one place and focus more on technological innovation. Furthermore, we employ advanced inventory management technologies to provide effective inventory solutions and maintain a strict quality management process to ensure product quality. With a modern logistics management system and strategic geographical positioning, we shorten delivery times and ensure timely component delivery.

PEW: *If the supply chain is a major industry challenge right now, so is the skills shortage. Are there any ways in which you can help customers address this issue, or is this outside of your company remit?*

WS: At WIN SOURCE, we recognize the significant impact that skills shortages may have on our customers' business operations, especially in fields such as automotive electronics, 5G communication, and the Internet of Things (IoT). While our primary responsibility is as a distributor of electronic components, we are also striving to help customers alleviate this issue through a series of measures.

Firstly, we assist customers in overcoming challenges arising from skills shortages by providing technical support and services. Our engineering laboratory department and field application engineer team are equipped with advanced testing and diagnostic equipment, enabling us to offer services ranging from simple component testing to complex system-level problem-solving solutions. This technical support can provide customers with the necessary assistance when they lack specific skill resources.

Secondly, we enhance customers' technical knowledge and operational skills through training sessions and seminars. These activities typically focus on the latest electronic component technologies, market trends, and supply chain management practices, helping to update knowledge and enhance skills within customers' teams. Our business modules also encompass the latest industry news and resource sharing, which we provide through our website, seminars, and customer services.

Furthermore, as active participants in the electronic distribution field, WIN SOURCE is committed to maintaining close connections with industry

experts throughout the supply chain. We are not only members of industry associations such as the Electronic Reuse Industry Association (ERAI), the National Manufacturing Institute (NMI), and the International Printed Circuit Association (IPC), but we also closely monitor international developments and industry standard changes through these platforms. This deep industry engagement enables us to stay abreast of industry trends and technological advancements, thereby helping our customers better address challenges such as skills shortages and ensuring they remain competitive in the fiercely competitive market.

While directly addressing skills shortages may fall beyond our core responsibilities, at WIN SOURCE, we are dedicated to providing support to our customers through various means. We firmly believe that by offering advanced technical support, resource sharing, and industry engagement, we can effectively support our customers and ensure their competitiveness in the ever-changing market.

PEW: *Sustainability, CSR and ESG – big topics right now. What do you do as an organisation both internally to address these issues, but also to help customers with their own policies in these areas?*

WS: At WIN SOURCE, we deeply understand the importance of sustainable development, corporate social responsibility, and Environmental, Social, and Governance (ESG) principles, and we actively implement policies and measures in these areas. Through these efforts, we not only improve the environmental performance of our company but also optimize social and economic performance, ensuring that our business activities promote social welfare while also protecting the natural environment and achieving long-term sustainable development goals. Additionally, we are committed to helping customers develop and implement strategies in these areas.

Internally, we have obtained environmental certifications such as ISO 14001 and ISO 9001:2015, demonstrating our commitment to sustainable development by reducing the environmental impact of our supply chain activities. Furthermore, we adhere to a people-oriented philosophy, providing employees with a fair and inclusive work environment, competitive salaries, and various outstanding welfare programs. We also conduct monthly training to enhance employees' professional skills and knowledge, demonstrating our commitment to talent cultivation and development.

Most importantly, customers can submit their inventory lists or stock through our website's online shopping platform, and our experts will evaluate the value and condition of their inventory within 24 hours and provide the most favorable quotation. Customers can then choose from a combination of three options: "bulk purchase," "off-site consignment," or "on-site consignment" to effectively clear excess inventory. This measure not only helps customers manage inventory but also significantly reduces electronic waste, contributing to environmental protection.

Moreover, we take a customer-centric approach and work closely with customers to help them develop or strengthen policies in these critical areas. Firstly, we share our best practices and experiences to help customers understand the importance of sustainable development and social responsibility

Moreover, we take a customer-centric approach and work closely with customers to help them develop or strengthen policies in these critical areas. Firstly, we share our best practices and experiences to help customers understand the importance of sustainable development and social responsibility. This includes providing specific advice on how to effectively implement environmental protection measures, improve energy efficiency, and optimize resource utilization in business operations.

Secondly, we provide customized solutions to support customers' specific needs, which may include helping them obtain relevant environmental management system certifications such as ISO 14001 or supporting them in implementing ESG principles in product design and supply chain management. Additionally, we enhance customers' teams' understanding of and response strategies to ESG trends through seminars and training sessions, which typically focus on industry regulations, market trends, and technological innovations.

PEW: *Before we finish, it would be great if you can share any insights you might have in terms of the power electronics market – whether that's the technologies and products being used, vertical market opportunities, expanding application areas, and the overall direction of travel?*

WS: The power electronics market is currently experiencing a period of dynamic change and technological innovation, and WIN SOURCE, as an influential distributor of electronic components in this field, is fortunate to witness and participate in these transformations.

Currently, the primary technological advancements in the power electronics market focus on improving efficiency and reducing equipment size. Particularly, wide-bandgap semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN), known for their excellent thermal performance and high efficiency, are gradually replacing traditional silicon materials. These materials enable devices to operate at higher temperatures and voltages, significantly enhancing power conversion efficiency. As a distributor of electronic components, WIN SOURCE not only possess obsolete & EOL, common-used, and shortage components, but also continuously introduces such semiconductor products to meet the demands of new markets such as 5G and electric vehicles.

As these technologies mature and their application areas expand, we are actively exploring emerging markets such as smart homes and the Internet of Things (IoT). These areas require high-performance electronic components to support technological advancements and industry development, and WIN SOURCE is helping customers seize these opportunities by providing efficient solutions and high-quality components.

Overall, power electronics technology is rapidly advancing towards higher efficiency, environmental friendliness, and intelligence. With the increasing demand for environmental protection and energy conservation in the market, power electronics products are gradually adopting more sustainable materials and technologies.

WIN SOURCE is committed to leveraging our deep industry knowledge, extensive product portfolio, and rapid adaptation to new technologies to meet these challenges and opportunities, thereby driving the development of the entire industry. We look forward to exploring more opportunities with global customers and partners and jointly promoting the advancement of power electronics technology.

PEW: *Any final thoughts as to the major challenges and opportunities facing both the power electronics sector as a whole and WIN SOURCE Electronics in particular?*

In the field of power electronics, WIN SOURCE is facing a series of challenges and opportunities. Through continuous innovation and optimization strategies, we actively respond to the rapid changes in the market and development needs.

We are well aware that the rapid development of the power electronics industry presents both significant challenges and enormous opportunities for our business. Especially with the rapid expansion of applications in consumer electronics, medical electronics, electric vehicles, robotics, and the continuous emergence of new technologies and products, the market's demand for more efficient and smaller electronic components continues to grow.

This drives us to continuously update and expand our product lines to adapt to these technological advancements. In this way, WIN SOURCE can effectively meet the growing market demand and actively explore larger market spaces, maintaining a leading position in the market with our extensive product supply and robust supply chain network. However, global trade policies and geopolitical turmoil also bring considerable challenges, particularly in supply chain management uncertainty. We recognize that enhancing the stability and efficiency of the supply chain is crucial. We have taken multiple measures to manage this uncertainty, including establishing closer partnerships with global suppliers, expanding global sourcing channels, enhancing supply chain transparency, and utilizing advanced logistics and inventory management technologies to optimize the supply chain's responsiveness and flexibility.

Additionally, we are striving to expand and strengthen our international business and global supply chain capabilities, especially in the power electronics markets of the Asia-Pacific, Europe, and North America. By leveraging local resources and market knowledge, we plan to provide more customized solutions for customers to enhance our existing market service capabilities and better meet customer needs and expectations.

In conclusion, despite the ongoing challenges, with our global supply chain management capabilities and profound understanding of market demand, WIN SOURCE is ready to seize the opportunities brought by these challenges, drive the development of the power electronics industry, and help our customers succeed in this ever-changing technological field.

Your head start through transparency:

Our data in your system

WÜRTH ELEKTRONIK has developed a REST API to supply customers' ERP or production planning software directly with data. This involves article data and data sheets for electronic and electromechanical components, and reliable live access to information on availability and stock-levels.

PLANNING gets a head start if you don't have to ask Würth Elektronik every time for the delivery time or current/future stock of required components, but you can call this up in your own system.

Automation of data queries saves valuable time. The part of the supply chain served by Würth Elektronik becomes far more transparent, and information is immediately available when it's needed.

Supply chain problems show time and again: Plannable production requires necessary information on the availability of the needed components. Würth Elektronik – as the first manufacturer in the industry – allows insight into its current and future stock levels.

Customers are empowered to align their requirements for standard components from areas such as passive components, power modules, optoelectronics, electromechanics or radio and sensor technology, directly to the available quantities. Procurement and production planning become more predictable, as information is available in real time.

The API interface is designed on a customer-specific modular basis around the information required or the functions to be used in the respective software systems. The customer's IT department receives detailed documentation enabling it to implement data retrieval independently without it having to rely on external development support or third-party providers.

The following information packages are provided for selection via the API interface:

- Technical and commercial product information
- Current and future stock availability
- Individual prices (for the relevant contracts)

The next logical step in networking is to set up an EDI interface for automatically transferring documents such as orders, order confirmations, delivery notes and invoices. The combination of the REST API and EDI interface enables optimized planning and a fully automated ordering process. The API team at Würth Elektronik advises and supports customers in setting up the interface. Contact via the API landing page or send us an e-mail at: customerAPI@we-online.de

To promote your products and services contact:
Shehzad Munshi
T: +44 (0)1923 69015
E: shehzad.munshi@angelbc.com

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