# POWER ELECTRONICS EUROPE

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## POWER GAN

# Power GaN Can Revolutionize the Industrial World


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## COVER STORY


## Power GaN Can Revolutionize the Industrial World

Two major application areas in the next industrial revolution are motors/motor drives and robotics/robots. GaN-based design and technical features in these areas keep factories competitive, flexible, efficient and optimized as we meet growing customer demands. Industry 4.0 brings rise to an era of smart factory floors that synergize mass production capabilities with automation, robotics, and M2M communication. Modern factories and industrial spaces must be increasingly intelligent and efficient with capital, costs, and energy, whether it's for pharmaceuticals, chemical, transportation, medical devices or fulfillment centers. However, power system design is reaching the theoretical limits of Silicon-based power devices. With its smaller, more energy-efficient and cost-effective capabilities, gallium nitride (GaN) plays a leading role in Industry 4.0.
More details on page 24.

Cover image supplied by GaN Systems, Canada

# Automotive Adopts Silicon Carbide

Though a significant slowdown of the market has been observed in 2018, "the boom is over for the time being", a CEO recently said, discrete power devices represent an established mature market with a value of about $13.5 billion in 2018 and an expected 2018 - 2024 CAGR of 2.9 %. Users look for low cost per device, a large selection of products and suppliers, and use of proven, highly standardized products, including packaging technologies. Major changes in packaging solutions will be realized on the electrical interconnections level, due to the growing adoption of copper clips as a substitute for more conventional wire and ribbon bonding. The adoption of wide-bandgap semiconductor die technologies (SiC and GaN) brings new innovative packaging solutions (high-temperature epoxy, low-inductance electrical interconnections, silver sintering die attach, etc.). Although the adoption of wide-bandgap devices calls for innovative packaging schemes and solutions, their impact on the packaging materials market will be rather limited due to the still small share of SiC and GaN technologies compared to Silicon, and the smaller die size compared to Silicon devices. Nevertheless, SiC devices are gaining the confidence of many customers and are penetrating various applications such as automotive, as various statements around PCIM Europe 2019 confirmed. This is also confirmed by the promising market outlook for SiC devices, which will reach a compound annual growth rate (CAGR) of 31 % for the period 2017 - 2023. Yole's forecast for the value of the SiC power semiconductor market is about $1.5 billion by 2023.

PCIM 2019 once again closed with an excellent result in its 41st year. 515 exhibitors on an area of 25,000 square meters, more than 12,000 trade visitors, and 800 conference delegates underlines the international role of this event. In responding to recent announcements of automakers to invest heavily in electric mobility US-based Cree announced at PCIM it will invest up to $1 billion in the expansion of its Silicon Carbide capacity with the development of a state-of-the-art, automated 200 mm fabrication facility and a materials mega factory at its campus headquarters in Durham. Upon completion in 2024, the facilities will substantially increase materials capability and wafer fabrication capacity up to 30-fold compared to Q1 of fiscal year 2017, which is when Cree began the first phase of capacity expansion. Right after PCIM on May 10 Cree announced an other major milestone in penetrating the automotive market due to Volkswagen's new strategy in electro mobility. The company has been selected as the exclusive Silicon Carbide partner for the Volkswagen Group's "Future Automotive Supply Tracks Initiative (FAST)". The aim of FAST is to work together to implement technical innovations quicker than before and to realize global vehicle projects more efficiently and effectively. This agreement connects two simultaneous revolutions - the automotive industry's move from internal combustion engines to EVs and the growing adoption of SiC in the semiconductor market.

Regarding European activities, the Horizon 2020 program's goal is to establish the world's first 200 mm pilot production facility for power electronics based on SiC, an advance on the existing standard of 150 mm. Nowadays worldwide SiC wafer production is still limited at 4 or 6 inches only and its state of the art availability is still limited to small-scale production due to several scientific/technical challenges. REACTION will build the first worldwide and European 8-inch SiC wafer pilot line facility for power technology. "The project will re-set European competitiveness, rearranging worldwide factories competition at the 8-inche wafer level, cancelling the gap and making the new silicon carbide technology industrially mature. This will enable European industry to set also the world reference of innovative and competitive solutions for critical societal challenges, like Energy saving and carbon dioxide reduction as well as sustainable environment through electric mobility and industrial power efficiency. It will have a terrific potential impact on the semiconductors market, on the continental value-chain of system applications as well as on the European semiconductors manufacturing strength. This will include the IP assets gained during the build-up phase, with a positive fall-out on business and job creation", Project coordinator Angelo Alberto Messina from ST Microelectronics expects. Through this program, the European Commission is investing €46.5 million over 42 months in the capabilities required to scale up production of SiC-based power electronics. Participants in the REACTION Horizon 2020 program represent the entire value chain for power electronics. The mission is to demonstrate the possibility of scaling the mass production of 200 mm substrates for SiC devices in power applications ranging from 600 V to 3.3 kV. The ultimate goal is to achieve the cost, performance and size requirements that will enable their broad adoption in emerging clean technology applications, including electric cars, renewable energy systems and smart power grids. Engineered materials and optoelectronic component maker II-VI Inc of Saxonburg, PA, USA, providing SiC substrates for power electronics, is to supply 200 mm SiC substrates under the REACTION programme, which started in November 2018.

It will be interesting to see whether Europe is able to build up such an advanced SiC capability under the pressure of US-based or even Chinese companies, which have made significant investments in SiC substrate and epi-wafer manufacturing, nearly doubling global capacity, with additional expansions announced for coming years.

**Achim Scharf**
**PEE Editor**

# Packaging – Big Opportunity for Materials Suppliers

Discrete power devices represent an established mature market with a value of about $13.5 billion in 2018 and an expected 2018 - 2024 CAGR of 2.9 %. Amongst the discrete power device industry's key characteristics and needs are low cost per device, a large selection of products and suppliers, and use of proven, highly standardized products and technologies, including packaging technologies. According to Yole Développement's analysis, the discrete power packaging market's evolution will remain pretty flat, but continue to grow at a 2018 - 2024 CAGR of 1.1 %. Global discrete power device packaging will reach $3.7 billion by 2024. Major changes in packaging solutions will be realized on the electrical interconnections level, due to the growing adoption of copper clips as a substitute for more conventional wire and ribbon bonding. The interconnections market will grow at a 2018 - 2024 CAGR of 2.5 %. Milan Rosin, Principal Analyst at Yole Développement, researched the power packaging landscape.

The packaging technologies for discrete power devices (leadframe, die attach, electrical interconnections, and encapsulation) should have the aforementioned characteristics. It is difficult to match the high-volume, standardized products and low cost required by device integrators with the acceptable additional costs equated to innovative packaging technologies. Market growth and market size for different packaging solutions is the complex result of many different variables, including device demand evolution, die size, package type and interconnection method used, device size following downsizing trends, semiconductor content per packaged device and more. Some of these factors favor a market increase, others a market decrease, participating in a rather flat market evolution.

The choice of packaging solutions and semiconductor die are increasingly interlinked. The adoption of wide-bandgap semiconductor die technologies (SiC and GaN) brings new innovative packaging solutions (high-temperature epoxy, low-inductance electrical interconnections, silver sintering die attach, etc.). However, most technological development in silicon, SiC, and GaN power device packaging is focused on other device types which by definition do not belong to the category of discrete devices: these include power modules and integrated devices like System-on-Chip (SoC) and System-in-Package (SiP).

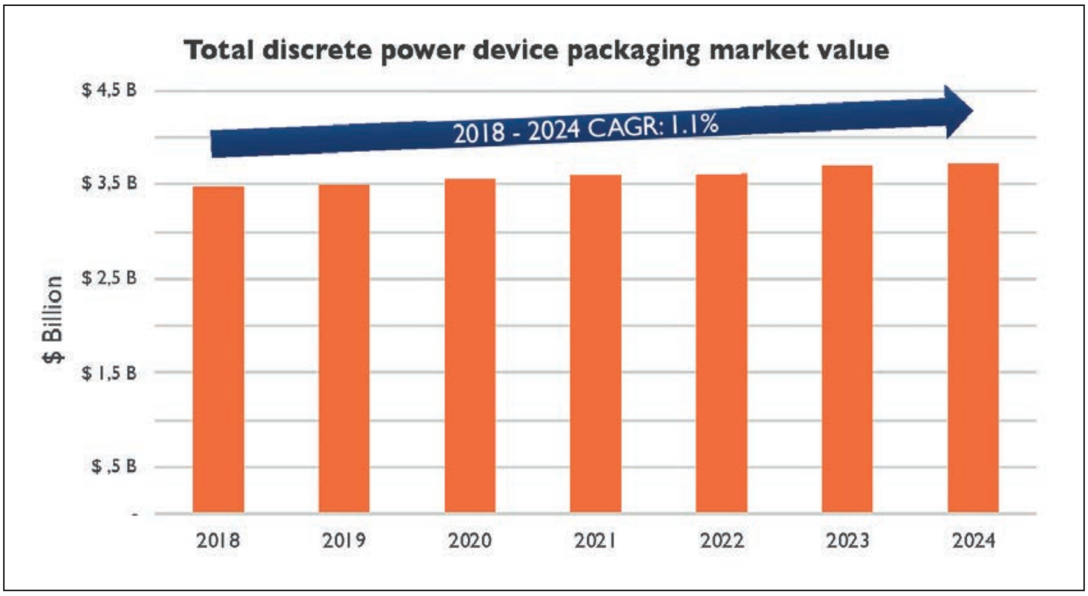
In these devices, the package holds much greater importance than in discrete devices. Developers of innovative packaging solutions focus on these devices because of stronger requirements, higher added-value for customers, and stronger differentiating value compared to competitors' products.

The progressive transition from discrete SiC towards SiC modules in EV/HEV applications, the embedded-die packaged systems, and the integration of GaN devices in multichip systems are just a few examples of such trends. Although the adoption of wide-bandgap devices calls for innovative packaging schemes and solutions, their impact on the packaging materials market will be rather limited due to the still small share of SiC and GaN technologies compared to Silicon, and the smaller die size compared to Silicon devices. Consequently, innovative packaging technology solutions will only have a minor impact on the discrete power device packaging market.

Discrete device makers (i.e. Infineon, ON Semiconductor, ROHM Semiconductor, Fuji Electric) can manufacture power devices internally or by subcontracting the packaging to outsourced semiconductor assembly & test (OSAT) companies. Once the demand for units becomes important, the devices manufacturers license the technology to other companies or use OSATs. Die-attach materials, epoxy molding compounds, and interconnection materials are typically supplied by the same materials suppliers, which also provide these solutions to other markets (power modules, multichip devices, etc.). Leadframes are supplied primarily by numerous Asian materials suppliers, since low cost and high volumes are important factors. With increasing application requirements (i.e. thermal cycling capability in electric vehicles), along with reducing device size and increasing device package-design complexity, players that can provide specific solutions and ensure tight angular and dimensional tolerances in high-volume production are increasingly sought by device packaging companies.

Advanced packaging companies like Amkor, ASE, Carsem, and UTAC have significant experience in the packaging of various complex devices for smartphones and microelectronic applications. Power electronics, especially at low and mid-power range, represents an opportunity for them to adapt and transfer their existing advanced packaging solutions to power devices, and thus enlarge their product and customer portfolio. "Advanced packaging solutions' highest added-value is not in 'rather simple' discrete devices, but in devices integrated with a driver, multichip devices, etc. Nevertheless, it is worth following the transformation trends in advanced packaging towards power devices, in order to not miss out on the growing business opportunities in discrete power device packaging", Milan Rosina concludes.

**www.yole.fr**




**Packaging market segments analyzed: leadframe, electrical interconnections, die attach and encapsulation**
**Source: Yole Développement, April 2019**

# SiC MOSFET Comparison 2019

SiC devices are gaining the confidence of many customers and are penetrating various applications. This is confirmed by the promising market outlook for SiC devices, which will reach a compound annual growth rate (CAGR) of 31 % for the period 2017 - 2023. The forecast for the value of the SiC power semiconductor market is about $1.5 billion by 2023.

Nevertheless, the technical panorama of SiC devices is still varying, and every manufacturer has its own solutions to die design and packaging integration. This leads to strong competition, which will accelerate technical innovation and lower prices. Moreover, SiC business models are still very different. In the future, we will see a restructuring of the supply chain driven by the main cost factors. Manufacturers propose different approaches for gate structure and device design, focused on SiC's intrinsic properties, or seeking to overcome issues linked to them. SiC-based MOSFET devices still have some technical and commercial challenges to face, despite the value they add. For example both SiC wafer processing and supply constraints impact wafer price and make it the major cost-driver of a SiC device. Other challenges include wafer size transition from 4-inch to 6-inch and beyond and the complexity of some process steps, mainly epitaxy, which hinder SiC adoption on a large commercial scale.

In a new report, System Plus Consulting presents an overview of the state of the art of SiC MOSFETs to highlight differences in design and manufacturing processes, and their impact on device size and production cost. 22 SiC MOSFETs of voltages varying from 650 V to 1700 V from Cree/Wolfspeed, ROHM, STMicroelectronics, Littelfuse, and Infineon have been analyzed. The report provides detailed optical and SEM pictures from the device's packaging and structure at the microscopic level of transistor design, with a focus on the latter. This report includes an estimated manufacturing cost of the MOSFET devices and analyzes their selling prices byReverse Costing, a process of disassembling a device (or a system) in order to identify its technology and calculate its manufacturing cost, using in-house models and tools. It provides physical, technological and manufacturing cost comparisons between the analyzed MOSFETs. Also the report shows an analysis of the actual SiC components' market.

**www.systemplus.fr**

# Power Technology Roadmap

The Power Sources Manufacturers Association (PSMA) announced the 2019 edition of the Power Technology Roadmap. The report, which forecasts the power technology and power delivery trends through 2023.

Included to the printed report comes an USB memory drive containing a record number of seventeen recorded webinars with up-to-date explanations of the information contained in the final report. The webinars add much to the presentation materials because the listener can hear and understand the context and the subtext of the original presentation in the speaker's voice. The recordings also capture the interesting and informative question and answer periods. In this edition a new section on University Research in Power Electronics has been added. University research provides a window into what products and technologies are in store for Power Electronics. Leading power electronics research universities were asked about their research areas and priorities and their responses were analyzed to extract most common research areas, least common/missing research areas and unique research areas. The overall structure of this year's PTR largely follows the format of and keeps the improvements made in the 2017 report. It offers a consolidated view of the latest trends in the power management, power control, and power delivery technologies by integrating the most recent inputs from webinars, surveys, analyses and discussions.

**www.psma.com/publications**

# Hope for Second Half 2019

Power Integration reports net revenues for the first quarter of $89.2 million, down 4 % from the prior quarter and down 13 % from the first quarter of 2018. But CEO Balu Balakrishnan expect strong sequential growth in the second quarter driven largely by increased demand from fast-charging applications in the smartphone market due to the arrival of USB PD technology. Revenues are expected to be $100 million for the second quarter of 2019.

He reflected FY 2018: After two consecutive years of double-digit revenue growth, our revenues declined by four percent in 2018. The decrease reflects, in part, a broad slowdown in demand afflicting the semiconductor industry in the latter part of the year. The downturn appears cyclical in nature, though it has undoubtedly been amplified by trade tensions as well as weaker domestic demand in China. These additional factors have been especially impactful in the smartphone and appliance markets, which account for roughly half of our total sales. In fact, revenues for our communications category, which is dominated by smartphone chargers and skews toward Chinese OEMs, declined nearly 20 % for the full year. The decline was driven not only by soft smartphone sales and associated inventory excesses in the supply chain, but also by slower adoption of fast chargers ahead of the upcoming transition to USB PD charging technology. Meanwhile, revenues from our consumer category, which is dominated by appliances, fell by about 6 % for the year reflecting weaker consumer demand in China as well as the impact of tariffs and the US-China trade dispute.

In the second half of 2018 we got a taste of what's to come, winning a design for a new USB PD tablet charger for a major OEM. Next, we expect continued strength in our industrial category, a bright spot for us in 2018 with growth of about 7 %. Our high-power gate-driver business, which makes up more than a third of the industrial category, grew at a double-digit rate for the second straight year driven by strength in renewable energy, electric locomotives and energy exploration. "We are seeing particularly healthy demand for high-power products in China, where spending on infrastructure such as rail and power-grid projects is likely being used to offset weaker consumer demand. We see even greater opportunity in the appliance market following the November launch of our BridgeSwitch motor-drive products. The introduction of BridgeSwitch adds a fourth major product category to our high-voltage product portfolio – in addition to our AC-DC power-conversion chips, high-voltage LED drivers and high-power gate-drivers – and expands our addressable market by approximately half a billion dollars", Balu Balakrishnan expects.

**Power Integrations' CEO Balu Balakrishnan expects strong sequential growth in the second quarter driven largely by increased demand from fast-charging applications and in the appliance market**

**Photo: AS**

BridgeSwitch products are highly integrated motor-drive ICs, addressing brushless DC motors up to about 300 watts (see PEE 1/2019, pages 27 – 29).

**www.power.com**

# Rising Demand for Display Drivers

Unit shipments of driver integrated circuits (ICs) declined 3 %, year over year, to reach 7.9 billion units in 2018, while revenue rose 0.4 % to reach $6 billion. As the average unit price of driver ICs continues to fall, revenue will also decline to $5.9 billion in 2019. In 2022, demand for driver ICs will once again grow to 7.7 billion units, but lower prices mean revenue growth will remain in negative territory, market researcher IHS expects.

Display module demand is saturated for LCD TVs, desktop monitors, notebook PCs, tablets, smartphones and other major applications, which has decreased demand for driver ICs through 2021. However, as unit shipments of 8K TV panels rises to 10 million units in 2024, driver IC demand will also start to increase. Even so, driver IC revenue will continue to decline, as Chinese companies invest more aggressively in the market, which will drive prices even lower.

TV panels use the most driver ICs of any application. In fact, 30 percent of all driver ICs are used in televisions. It's important to note that displays with higher definition require more driver ICs than displays with lower resolution. Generally speaking one full-high-definition (FHD) TV requires 6 source driver IC chips, while an 8K TV panel requires 24 source driver IC chips.

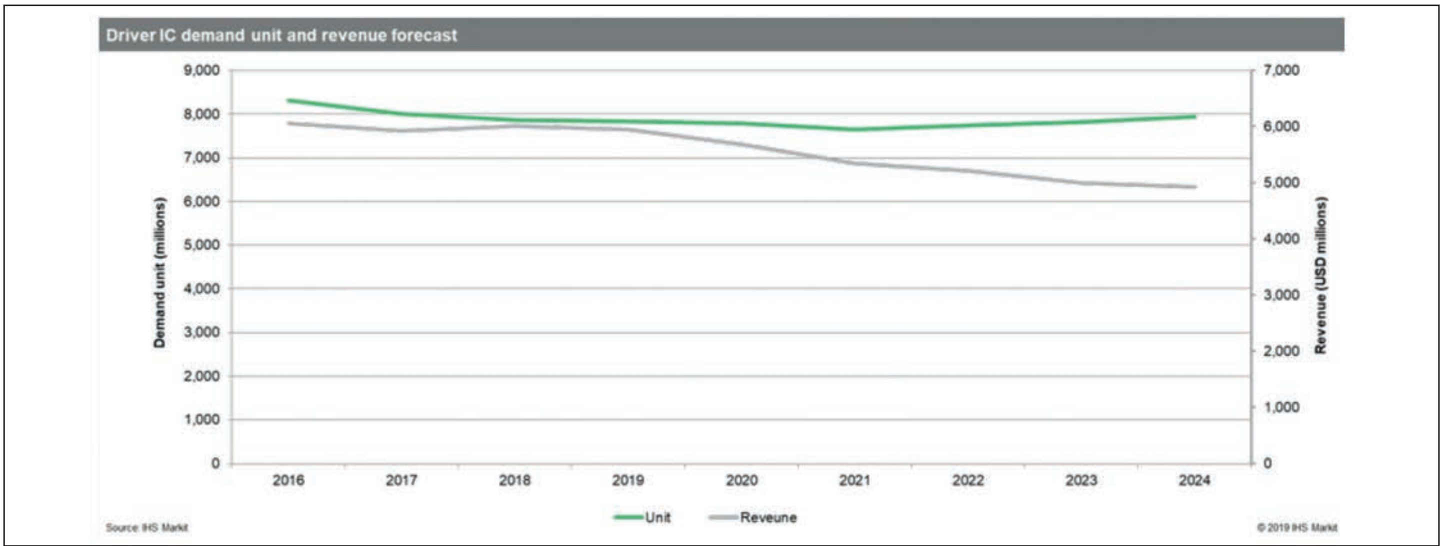
Half of all TV panels shipped in 2019 will be 4K panels, rising to 60 % in 2023. Consequently source driver IC demand will also increase this year. On the other hand, as more panel makers adopt gate-on-array (GOA), dual-rate-driving (DRD), triple-rate-driving (TRD) and other technologies, the number of driver ICs required per panel will fall. GOA will reduce gate driver IC demand, while DRD and TRD will reduce source driver IC demand. Also, total TV panel unit demand will saturate. Total Driver IC demand will decline slightly until 2021. Beginning in 2022, 8K TV panel will have a major impact on TV panel driver IC demand, causing demand to rise.

Smartphone driver IC demand accounts for approximately 70 % of the small and medium-sized display market. However, the smartphone market is also saturated, which will lead to sluggish growth in the future.

Overall driver IC supply has been tight for almost for three years, due to foundry capacity tightness. Chip-on-film (COF), which is used to bond the driver IC to the display panel, is in short supply, and driver IC supply stability has been an issue in the industry for many years. While driver IC unit prices have been stable for three years, the situation may change as driver-IC wafer capacity is expected to increase.

"In the coming years, mainland China will continue to focus on semiconductor development, in order to gradually decrease reliance on imports, which will lead to increased investment in wafer foundries. For example, Nexchip has already begun mass production in the second half of 2018, with an initial capacity of 10,000 sheets of 12-inch wafers per month, which will grow to 40,000 sheets per month in 2019. New fabless driver IC makers in China will also join the market, further increasing competion and leading to even lower prices in the coming years", concludes Vicki Chen, senior research analyst, IHS Markit.

**www.ihsmarkit.com**




# Challenging Market Environment Persists

Infineon performed well during the second fiscal quarter, despite a significant slowdown of the market. For the 2019 fiscal year Infineon expects to generate revenue of €8.0 billion, According to Reinhard Ploss, CEO of Infineon Technologies, the boom is over for the time being, the momentum in demand has weakened. "At the end of March, we responded to this trend by adjusting our outlook for the year and prepared for a lower level of growth. At the same time, we manage the current cycle and cut costs. We will continue to pursue strategic investment initiatives with the aim of safeguarding Infineon's future. This is driven by the long-term prospects in our key target markets, which include electro mobility, autonomous driving, renewable energy, data centers and mobile communications."

In the second quarter of the 2019 fiscal year, revenue grew by 1 % from € 1,970 million to € 1,983 million quarter-on-quarter. Revenue was up in the Automotive (ATV) and Digital Security Solutions (DSS) segments, marginally down in the Industrial Power Control (IPC) segment and somewhat more significantly down in the Power Management & Multimarket (PMM) segment. Operating profit amounted to €305 million, compared to €327 million in the previous three-month period.For the 2019 fiscal year as a whole, Infineon expects revenues of €8.0 billion. This corresponds to a forecast increase of just over 5 % over the previous fiscal year (€7.6 billion). Revenue growth in the Automotive and Industrial Power Control segments is expected to exceed the Group average, Power Management & Multimarket segment revenue is likely to grow at a slightly slower.

**www.infineon.com**

**Reinhard Ploss, CEO of Infineon Technologies: "The boom is over for the time being"**

# From Record to Record Figures

The leading international exhibition and conference for power electronics and its applications once again closed with an excellent result in its 41st year. From 7 - 9 May 2019, 515 exhibitors – 54 percent from abroad – presented the latest trends, developments and product innovations in power electronics on an exhibition area of 25,000 square meters. More than 12,000 trade visitors and 800 conference delegates took the opportunity to get informed by the exhibitors as well as by the conference sessions comprising around 300 papers. Next year's PCIM Europe will take place from 5 - 7 May 2020.

One of the highlights was the opening ceremony on May 7 including the presentation of the Young Engineer and Best Paper Awards. "The PCIM Conference and Exhibition serves the power electronics industry and academia by introducing new technologies to the market and discussing the latest research results and products during the conference. Over the years we have seen a strong development and the PCIM 2019 is the largest event in applied power electronics on a worldwide scale. Regarding technical directions digitally controlled power conversion systems will achieve higher power densities, higher efficiencies, and higher flexibility along with zero failure design for the specified lifetime", Conference Director Leo Lorenz pointed out. "After nine years of market growth this year faces due to political reasons and uncertanties a slowdown, nevertheless all market researchers estimate until the year 2030 a very healthy development – even in Silicon-based devices. But top highlights are wide bandgap technologies and devices. Here we see many emerging applications with outstanding performance and cost benefits at the system level, leading to outstanding market increase figures for wide bandgap devices by a factor ot 12, from 250 million dollars today up to 3 billion by 2030, split in two third for Silicon Carbide and one third for Gallium Nitride. Regarding industries the main drivers are automotive, sustainable energy supply and factory automation. New players are coming up from China, India and Korea. In particular China is not only the biggest market for power electronics, but also the most dynamic country in electro mobility, renewable energy technologies and artificial intelligence. These market trends are addressed here at the conference with more than hundred papers on wide bandgap technologies, new devices, and interesting new future applications. Also we have more than fifty papers on new materials, chip-


**PCIM 2019 opening featuring Best Paper and Young Engineer Awardees with sponsors; PEE Editor Achim Scharf (left), BPA winner Jürgen Schuderer, Semikron's Uwe Scheumann, Fred Lee for Mohamed Ahmed from Virginia Polytechnic Institute, Miguel Vivert from Pontificia Universidad Javeriana, Infineon's Jörg Malzon-Jessen, Mitsubishi's Gourab Majumdar, Christoph Marczok from Fraunhofer Institute IZM, ECPE's General Manager Thomas Harder, and PCIM's Conference Director Leo Lorenz Photo: Mesago/Uwe Mühlhäußer**

Best Paper Award handover by PEE's Achim Scharf (left), SEMIKRON's Uwe Scheuermann to ABB's Jürgen Schuderer (right) Photo: Mesago/Uwe Mühlhäußer

interfacing technologies for elevating temperatures and increasing reliability as well as innovative packaging for embedded power integration", Lorenz summarized the trends.

The awards reflected the sketched technological trends. Three Young Engineer Awards comprising € 1000,00 price money were given to Mohamed Ahmed, Virginia Polytechnic Institute and State University, USA, for "**GaN Based High-Density Unregulated 48 V to x V LLC Converters with ≥ 98% Efficiency for Future Data Centers**"; Christoph Marczok, Fraunhofer Institute IZM, Germany, for "**Low Inductive SiC Mold Module with Direct Cooling**"; and Miguel Vivert, Pontificia Universidad Javeriana, Columbia, for "**Decentralized Controller for the Cell-Voltage Balancing of a Multilevel Flying Cap Converter**". These awards were sponsored by ECPE, Infineon technologies and Mitsubishi Electric.

The Best Paper was awarded to Jürgen Schuderer, ABB Corporate Research, Switzerland, for "**High-Power SiC and Si Module Platform for Automotive Traction Inverter**". Price money for the latter was € 1,000 plus a trip to PCIM Asia 2020, sponsored by Power Electronics Europe and SEMIKRON. A short version of the awarded papers are published in our features section.

**Big push for WBGs**

In responding to recent announcements of automakers to invest heavily in electric mobility US-based Cree Inc. (**www.cree.com**) announced it will invest up to $1 billion in the expansion of its Silicon Carbide capacity with the development of a state-of-the-art, automated 200 mm fabrication facility and a materials mega factory at its campus headquarters in Durham, N.C. "This marks the company's largest investment to date in fueling our Silicon Carbide and GaN on Silicon Carbide business at our subsidary Wolfspeed. Upon completion in 2024, the facilities will substantially increase our materials capability and wafer fabrication capacity, allowing wide bandgap semiconductor solutions that enable the dramatic technology shifts underway within the automotive, communications infrastructure and industrial markets", expressed in a formal announcement Cree's CEO Gregg Lowe at PCIM. Cree/Wolfspeed is not only the leading SiC material supplier for Infineon Technologies, ST Microelectronics and others, but also for SiC devices such as MOSFETs and diodes.

"We see great interest from the automotive and communications infrastructure sectors to leverage the benefits of Silicon Carbide to drive innovation. However, the demand for Silicon Carbide has long surpassed the available supply. Thus we are announcing our largest-ever investment in production to dramatically increase this supply and help customers deliver transformative products and services to the marketplace," Lowe added. "This investment in equipment, infrastructure and our workforce is capable of increasing our wafer fabrication capacity up to 30-fold and our materials production by up to 30-fold compared to Q1 of fiscal year 2017, which is when we began the first phase of capacity expansion. We believe this will allow us to meet the expected growth in Wolfspeed's material and device demand over the next five years and beyond." Capacity will be added with the build out of an existing structure as a 253,000 square-foot, 200 mm power and RF wafer fabrication facility as an initial step to serve the projected market demand. The new North Fab is designed to be fully automotive qualified and will provide nearly 18 times more surface area for manufacturing than exists today, initially opening with the production of 150 mm wafers. The existing Durham fabrication and materials facility will converted into a materials mega factory. "These manufacturing mega-hubs will accelerate the innovation of today's fastest growing markets by producing solutions that help extend the range and reduce the charge times for electric vehicles, as well as support the


Cree's CEO Greg Lowe announced at PCIM a $1-billion-investment in SiC/GaN materials and device fabrication Photo: AS

Automotive and in particular elecro-mobility played a major role at PCIM 2019, especially announcements from Infineon and Cree to invest in EV powertrains
Photo: Volkswagen AG

rollout of 5G networks around the world," Lowe underlined. "We believe that this represents the largest capital investment in the history of Silicon Carbide and GaN technologies and production with a fiscally responsible approach. By using existing facilities and installing a majority of refurbished tools, we believe we will be able to deliver a state-of-the-art 200 mm capable fab at approximately one-third of the cost of a new fab."

Also Japanese ROHM (**www.rohm.com**) plans a new building for more SiC production capacity by factor 19. The company is aiming for a top market share for SiC wafers and components. "To achieve this goal, production capacity must be greatly increased. To this end, production efficiency is to be improved by further increasing the wafer size and using the latest equipment.

According to Wolfspeed's CTO John Palmour customers does not care about planar or trench, their major concern is cost Photo: AS

Secondly, building the new factory or building is also required", said Toshimitsu Suzuki, new President of ROHM Semiconductor Europe. The new three-storey building at Apollo will increase the production area by approximately 11,000 m$^2$ by the end of 2020.

**Automotive goes SiC**

Right after PCIM on May 10 Cree announced an other major milestone in penetrating the automotive market due to Volkswagen's new strategy in electro mobility. The company has been selected as the exclusive Silicon Carbide partner for the Volkswagen Group's (**www.volkswagen.de**) "Future Automotive Supply Tracks Initiative (FAST)". The aim of FAST is to work together to implement technical innovations quicker than before and to realize global vehicle projects more efficiently and effectively. "The Volkswagen Group has committed to launch almost 70 new electric models in the next ten years, which is up from our pledge of 50 and increases the projected number of vehicles to be built on the Group's electric platforms from 15 million to 22 million in that timeframe. Our FAST partners are our strategic partners, each of them outstanding in their respective field. We want to shape the automotive future together," stated Michael Baecker, Head of Wolfsburg-based Volkswagen Purchasing Connectivity.

This agreement connects two simultaneous revolutions - the automotive industry's move from internal combustion engines to EVs and the growing adoption of SiC in the semiconductor market. This accelerates the automotive industry's transformation to electric vehicles, enabling greater system efficiencies that result in longer range and faster charging, while reducing cost, lowering weight and conserving space. The Volkswagen Group and Cree will be working with tier-one and power module suppliers to engineer SiC-based solutions for future Volkswagen Group vehicles.

But Volkswagen is not the only one to implement SiC in future cars, already today the Tesla model 3 drive inverter is equipped with SiC MOSFETs in the power stage, coming from an supply agreement with STMicro (**www.st.com**) delivering the power modules to Tesla. "We have recently announced three wafer supply agreements inclding Infineon and STMicro, a half billion dollar multi-year contract on 150-mm-substrates in the voltage range between 650 V and 1200 V", Wolfspeed's (**www.wolfspeed.com**) CTO John Palmour stated.

SiC supply can not only addressed by capacity expansion. "We also try to shrink the die size and to maximize the yield on the wafer, but not by moving to trench technology. Indeed, we achieve the lowest on-resistance compared to any trench – even double trench. Customers does not care about planar or trench, their major concern is cost. And by reducing die size the heat becomes a problem, how to remove it. Dual-sided cooling or copper bonding could solve this problem", Palmour underlined. "150-mm-wafers will be the dominant size over the next 4 to 5 years, since all the major semiconductor companies have built their dedicated SiC lines around this size, and then when the EV market really starts to turn on 200 mm will come into play". This statement is valid for Infineon – the company is one of Cree's major SiC wafer customers. "We will be ready to process 200-mm-SiC-Wafers as soon as they will be there", said Peter Waver, Head of Infineon's Industrial Power Control Division.

Infineon (**www.infineon.com**) offers a broad range of semiconductors for electro-mobility - from bare dies, discrete components, chips embedded in printed circuit boards, to power modules; the portfolio includes products based on Silicon as well as on Silicon Carbide. So far power modules control the electric drive in Volkswagen's modular electric drive matrix MEB, which is the industry's largest electrification platform. Most of coming EVs will be based on the MEB, including the new ID. family from the Volkswagen brand, as well as models from Audi, Seat and ?koda. As part of FAST, Infineon and Volkswagen will also discuss future semiconductor requirements. "Cooperation with strong partners is a key factor for the success of our electric offensive", VW's Michael Baecker stated. "Our e-models feature technologies and ideas from the most innovative companies in our industry". "Together with our customers, we want to ensure that electro-mobility becomes part of people's everyday life", added Peter Schiefer, President of the Automotive Division of Infineon. "Together with Volkswagen, we can identify requirements early on and create innovations

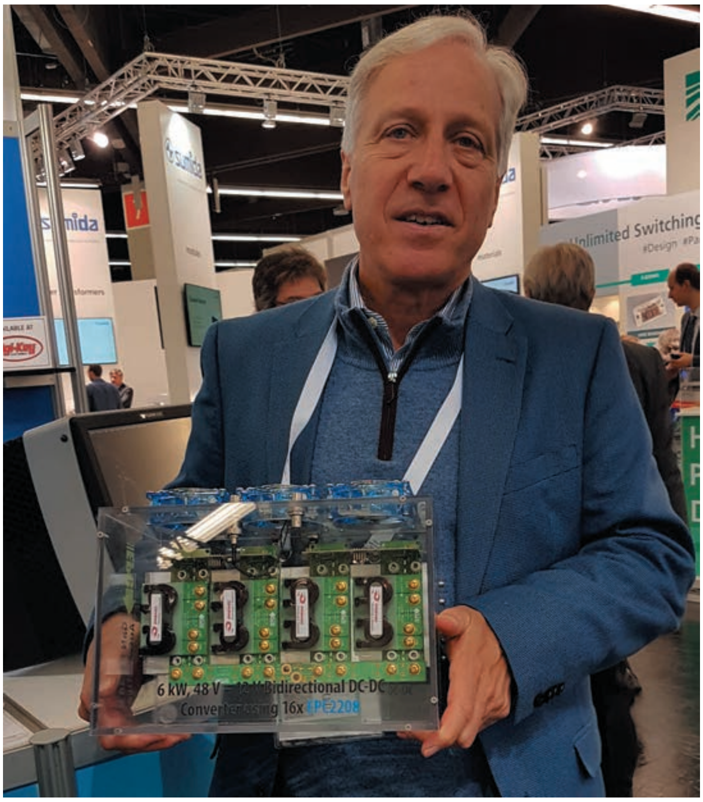
**Infineon's Peter Schiefer will ensure that electro-mobility becomes part of people's everyday life**

that increase the range of electric vehicles or reduce charging times, for example."

In 2018, 15 of the 20 top-selling electric models and plug-in hybrid vehicles worldwide used Infineon's components, in particular the so-called Hybrid Pack power modules, available in IGBT- and SiC-versions. In order to cater for growing demand for power electronics in the automotive industry as well as other sectors, Infineon is expanding its production capacities at its existing plants in Dresden (Germany) and Kulim (Malaysia). Over the coming years, the company is also investing € 1.6 billion in a new power semiconductor fab in Villach (Austria) scheduled to go into operation in 2021.

**Alternative Gallium Nitride**

EPC (**www.epc-co.com**) announced AEC-Q101 qualification of the 80 V eGaN transistor EPC2214 designed for lidar systems (Light Detection and Ranging) in the automotive industry and other harsh environments. The EPC2214, an 80 V, 20 mΩ, eGaN FET with a 47 A pulsed current rating in a tiny 1.8 mm² footprint, is suited to use for firing the lasers in lidar systems because the FET can be triggered to create high-current with extremely short pulse widths. This new device has completed rigorous automotive AEC-Q101 qualification testing and will be followed with several more discrete transistors and integrated circuits designed for the harsh automotive environment. EPC's eGaN FETs underwent rigorous environmental and bias-stress testing, including humidity testing with bias (H3TRB), high temperature reverse bias (HTRB), high temperature gate bias (HTGB), temperature cycling (TC), as well as several other tests. EPC's WLCS packaging passed all the same testing standards created for conventional packaged parts, demonstrating that the performance of chip-scale packaging does not compromise ruggedness or reliability. These eGaN devices are produced in facilities certified to the Automotive Quality Management System Standard IATF 16949.




**EPC's Alex Lidow showed an inverter for 48-V-automotive applications, i. e. for mild hybrids** **Photo: AS**


**GaNSystem's new 150-A-device shown in a traction inverter reference design and 75 kW power module** **Photo: AS**

Based on the experience with 48-V applications in servers at PCIM CEO Alex Lidow showed an inverter for 48-V-automotive applications, i. e. for mild hybrids. "We already have signed six contracts with automotive tier-1 suppliers", he noted.

GaN Systems (**www.gansystems.com**) demonstrated the new 650 V, 150 A GaN power transistor. "The GS-065-150 device has 100 times lower switching losses than comparable IGBTs – that's two orders of magnitude less, a 99 % reduction in switching losses", said CEO Jim Witham. In addition systems from customers and partners, with many now in production, have been shown. Based on the 150-A-device a traction inverter reference design and 75 kW power module (Silvermicro) gained a lot of attraction. Nanjing-based Silvermicro Electronics focuses on design and manufacturing power IGBT and MOSFET modules.

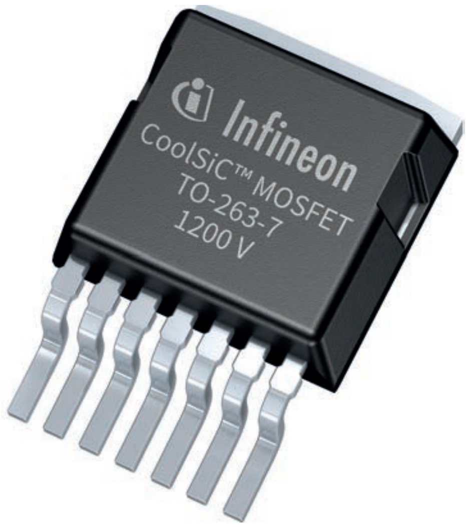
"Now is a great time to be in the power industry. Every 20 years or so there is an inflection point, which is now with GaN power devices", said Paul Wiener, VP Marketing. "Coming from the Applied Power Electronics in the USA where we saw overwhelming momentum in GaN acceptance and implementation, that enthusiasm has been continued at PCIM." **AS**

# More Power on the Exhibition Floor

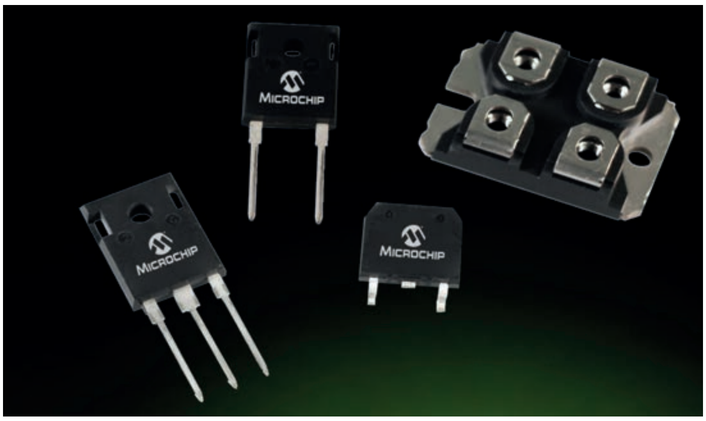
PCIM Europe's 515 exhibitors presented a broad range of products of high interest for the system designer. Here also new power semiconductors played the major role.

**Power Semiconductors**

Infineon (**www.infineon.com/coolsic-mosfet**) announced volume production of 1200 V CoolSiC MOSFET devices. They are rated from 30 mΩ to 350 mΩ and implemented into TO247-3 and TO247-4 housings. The expansion includes a SMD portfolio and a 650 V CoolSiC MOSFET product family, both to be launched soon. CoolSiC trench technology features an exclusively high threshold voltage rating larger than 4 V combined with a low Miller capacitance. For this reason, CoolSiC MOSFETs exhibit high immunity against unwanted parasitic turn-on effects. Together with a turn-on gate-source voltage of +18 V with 5 V margin to maximum rated voltage of +23 V, the new discrete MOSFETs deliver an advantage over Si IGBTs or Superjunction MOSFETs. The robust body diode is rated for hard commutation.




Microchip (**www.microsemi.com/sic**) announced, via its Microsemi subsidiary, the production release of a family of SiC power devices complemented by a broad range of microcontrollers. The new 700 V SiC MOSFETs and 700 V and 1200 V SiC Schottky Barrier Diodes (SBDs) join the existing portfolio of SiC power modules. The over 35 discrete products that have been added to Microchip's portfolio are available in volume, supported by development services, tools and reference designs. The broad family of SiC die, discretes and power modules are offered across a range of voltage, current ratings and package types.The expanded SiC portfolio is supported by a range of SiC SPICE models, SiC driver board reference designs and a PFC Vienna reference design.




Nexperia (**www.nexperia.com/lfpak88**) announced a new package in its MOSFET and LFPAK family which, when combined with its latest Silicon technology, results in 40 V MOSFETs delivering a low on-resistance of 0.7 mΩ. LFPAK88 devices replace larger power packages such as $D^2PAK$ and $D^2PAK$-7, and measuring 8 x 8 mm offer a footprint reduction of 60 %, and a 64 % lower profile. LFPAK88 devices employ the copper-clip and solder die attach construction, resulting in low electrical/thermal resistance, good current spreading and heat dispersal. In addition, the thermal mass of the copper-clip also reduces hot-spot formation which results in improved avalanche energy and linear-mode (SOA) performance. The combination of high continuous and demonstrated current rating of 425 A presents power density of up to 48 times when compared to $D^2PAK$ devices and reliability levels more than two times better than is required by AEC-Q101.


ON Semiconductor (**www.onsemi.com**) launched a SiC based hybrid IGBT and associated isolated high current IGBT gate driver. The AFGHL50T65SQDC uses the latest field stop IGBT and SiC Schottky diode co-packaged to offer low conduction and switching losses. In multiple power applications, including those that will benefit from reduced reverse recovery losses, such as totem pole based bridgeless power factor correction (PFC) and inverters. The device is rated for 650 V operation and able to handle continuous currents up to 100 A @ 25°C (50 A @ 100°C) as well as pulsed currents up to 200 A. For systems requiring greater current capability, a positive temperature co-efficient allows for parallel operation. With junction temperatures as high as 175°C it is suitable for demanding power applications, including automotive AEC-Q101.

Alongside the new hybrid IGBT, a new range of isolated (greater than 5 kVrms) high current IGBT drivers have been shown. The NCD(V)57000 series are high-current single channel IGBT drivers (source 7.8 A drive current and sink 7.1 A) with internal galvanic safety isolation, featuring complementary inputs, open drain fault and ready outputs, an active Miller clamp, accurate undervoltage lockout, DESAT protection with soft turn off, negative gate voltage pin and separate high and low driver outputs.

SEMIKRON
innovation + service

# IGBT Generation 7

## The New Benchmark for Motor Drives

The generation 7 IGBTs are specifically designed to match the requirements of motor drive applications. They provide lower system costs thanks to reduced power losses and increased output power and power density.

For low/medium power motor drives available in MiniSKiiP and SEMITOP E1/E2 as CIB and sixpack. For medium/high power motor drives available in SEMiX 3 Press-Fit and SEMiX 6 Press-Fit in CIB and sixpack topologies.

**Features**

- Optimized IGBTs for motor drive applications
- Reduced saturation voltage and chip size
- Higher nominal currents
- Up to 45% more module output power
- Lower overall system costs

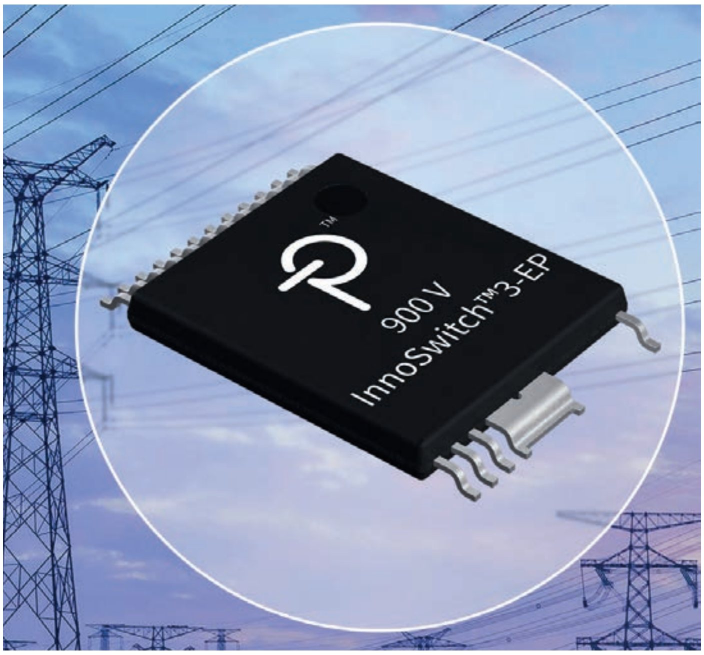
MiniSKiiP

SEMiX 3 Press-Fit

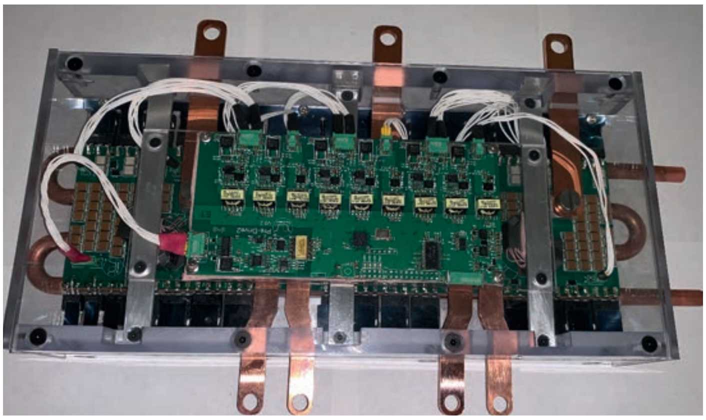
Analog Devices (**www.analog.com**) demonstrated small form factor isolated gate drivers are designed for the higher switching speeds and system size constraints required by power switch technologies such as SiC and GaN, while still providing control over switching characteristics for IGBT and MOSFET configurations. These isolated gate drivers incorporate iCoupler isolation technology combined with high speed CMOS and monolithic transformer technology to enable low propagation delay without sacrificing common-mode transient immunity (CMTI) performance. High pulse fidelity architecture enables motor power efficiency to meet new required efficiency levels, and superior timing performance stability reduces voltage distortion, as well as harmonic and output power content on solar inverters. A demonstration featured a DC/DC optimizer sub-system, employing half-bridge gate drivers that control GaN transistors at very high switching frequencies beyond 2 MHz.

Panasonic's (**http://industry.panasonic.eu**) 600 V X-GaN transistors provide superior switching performance and high reliability and robustness, thanks to their fast switching, highly conductive structure that suppresses current collapse. These benefits are demonstrated in new reference designs of a 3 kW totem pole PFC and of a 65 W active clamped flyback AC adapter. The company has developed a single chip GaN bi-directional switch capable of operating in 4 quadrants, by adopting an innovative dual gate device structure. This device enables a significant reduction of conduction losses and of the number of components needed in topologies such as multilevel inverters, matrix converters and Vienna rectifiers.

Power Integrations (**www.power.com**) announced a suite of offline switcher ICs incorporating 900 V primary MOSFETs. These devices include ICs for high-efficiency isolated flyback power supplies and for simple non-isolated buck converters. Applications include three-phase industrial power supplies up to 480 VAC, and high-quality consumer products destined for regions with unstable mains grids, tropical regions with frequent lightning strikes or any area where high-energy ring-waves and surges are prevalent. The new products include 900 V versions of the LinkSwitch-TN2 ICs for simple, non-isolated buck converters plus three new members of the flagship InnoSwitch3-EP IC family, which enable extremely high-efficiency isolated flybacks up to 35 W. The 900 V LinkSwitch-TN2 ICs deliver the lowest-component-count switcher solutions for buck converters. Devices feature selectable current limit and fully integrated auto-restart for short-circuit and open-loop protection.




Pre-Switch (**www.pre-switch.com**) announced its CleanWave 200 kW SiC automotive inverter evaluation system that enables power design engineers to investigate the accuracy of the company's soft switching architecture and platform over varying load, temperature, device tolerance and degradation conditions. The platform, including the Pre-Drive3 controller board, powered by the Pre-Flex FPGA, and RPG gate driver board, virtually eliminates switching losses, enabling fast switching at 100 kHz, significantly improving low torque motor efficiency.  High switching frequency also reduces motor copper and iron losses. For electric vehicles this results in a massive increase in range of 5-12 %. The soft-switching solution also benefits industrial motors, solar, wind and traction applications or any other power converter requirement greater than 100 kW that is looking to reduce costs and improve efficiency.



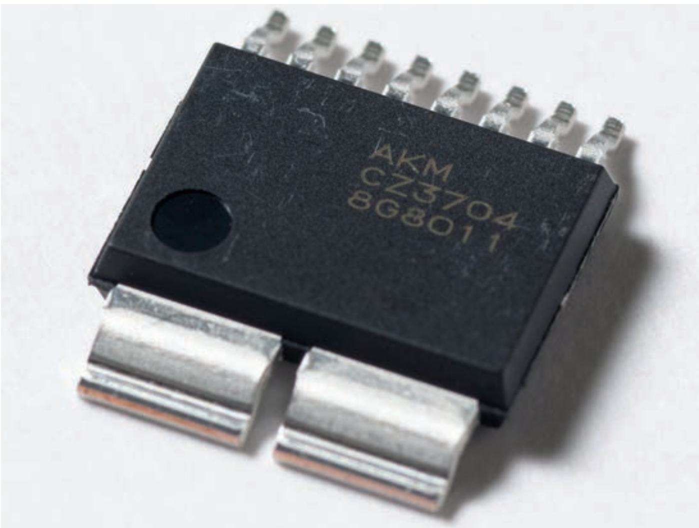
ROHM (**www.rohm.com/eu**) announced the extension of new automotive-grade SiC MOSFETs in its line-up, namely SCT3xxxxHR series. This AEC-Q101 qualified SiC MOSFETs are suited for automotive on-board chargers and DC/DC converters. Also the new series of Isolated Gate Driver ICs for SiC power MOSFETs improves the design of industrial and automotive power systems. The line-up has a 3,75 kV isolation, AEC-Q100 gate driver device specifically designed to drive SiC power MOSFETs. It has a built-in active miller clamping to prevent parasitic turn on effects and integrates an under-voltage lock-out (UVLO) optimized to drive ROHM's SiC MOSFET.

**Current Sensors**

Allegro MicroSystems (**www.allegromicro.com**) announced a new family of automotive AEC-Q100 qualified, monolithic Hall effect current sensor ICs. The ACS71240 family is intended for electric vehicle chargers, DC/DC converters, as well as industrial motor and IOT applications. These new devices offer output signal immunity to stray magnetic fields (created by adjacent motors or current carrying wires); improved output signal accuracy (1.5% typical); and output signal immunity to noisy supply voltage rails. The fast, dedicated over current fault output that has a typical response time of 1.5 µs, improving system safety. This fault output provides a simple means of detecting short circuit events that will prevent damage to MOSFETs or IGBTs in inverter, motor and other switching power electronics applications. The ICs can replace shunt resistors, operational amplifiers, current transformers and voltage isolators in applications that require small form factor.

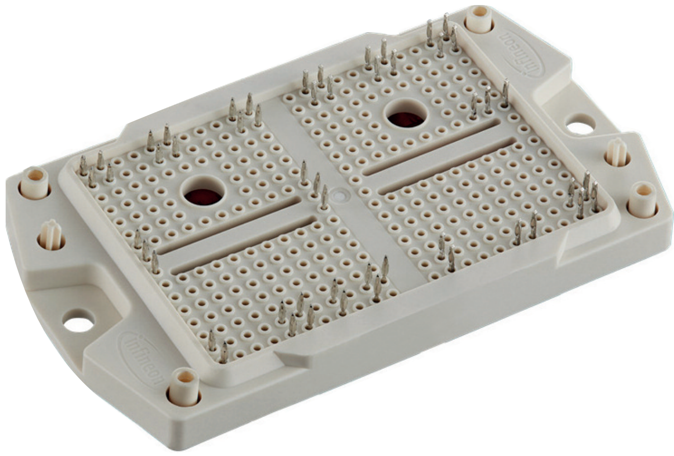
LEM (**www.lem.com**) introduced a Digital Integrator AI-PMUL for Rogowski coils. The Rogowski coils output voltage is proportional to the derivative of primary current. An electrical integrator circuit is therefore necessary to convert this signal, so it is proportional to the value of the primary current. This integrator is an essential component in current measurement with a Rogowski coil, and the amplification stage architecture and implementation have a major impact on the sensor's electrical performance such as linearity, phase-shift and frequency bandwidth. With a linearity error below 0.1 % and combined with LEM ART & ARU (coming soon) class 0.5 Rogowski coils, it offers a universal metering and monitoring solution with a measurement accuracy up to 5000 A. The integrator AI-PMUL covers in one universal product all the ratings. Users can select between 12 current ranges from 100 A to 5000 A. The setting of the current range, input sensitivity and output selection is made through push buttons and bi-colour LED.


Asahi Kasei Microdevices (**www.akm.com**) presentated the coreless current sensors of the CZ370x series, which complies with the product safety standard UL61800-5-1 and features a current detection range from ± 5 A to ± 180 A. Next to its maximum effective current of 60 Arms and low primary conductor resistance, its fast response time characteristics of less than 1 µs stand out as well as the stray magnetic field effect reduction. With the AK310x, AKM will also exhibit the newest addition to the coreless current sensor family, featuring highest level of low-noise characteristics.




**Power Modules**

Heraeus Electronics (**www.heraeus-electronics.com**) announced that its Condura product line has been enhanced with new features for Direct Copper Bonding (DCB) substrates to extend the lifetime of power electronics modules. DCB substrates are an essential component for the module production in power electronics. Now Heraeus Electronics has developed its proven Condura product line even further to support power electronics manufacturers. Additional services include an optimized design along with a special surface treatment to increase the service life of DCB substrates. Various patent-free shapes and layouts that can be individually adapted to customer requirements. An additional service is grinding, a special mechanical surface treatment that ensures optimized properties. Various degrees of roughness reduce unevenness and ensure an fitting surface.



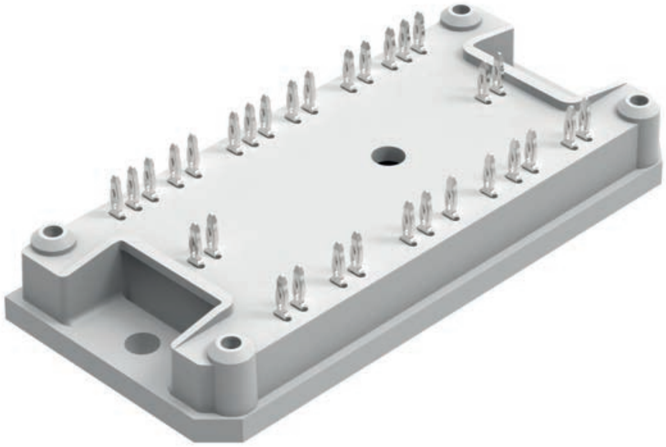
Infineon Technologies (**www.infineon.com/pcim**) extended its Easy family to include the Easy 3B, a platform to extend current inverter designs to achieve higher power without changing much on the mechanical side. At the same time, the new package inherits many of the advantages of the 1B/2B such as the pin-grid system, which is very important for customizing. The first module with the new package design is a 400 A, 3-level ANPC device aiming at 1500 V solar inverter applications. A Easy 3B with IGBT7 will address the industrial drives market, also a CoolSiC MOSFET version will be added. Also four new HybridPACK Drive modules optimized for different inverter performance levels between 100 kW and 200 kW as well as the Double Sided Cooling (DSC) S2 were on stage. This module targets main inverters up to 80 kW in hybrid and plug-in hybrid electric vehicles with high power density requirements. As a compact half-bridge module, the HybridPACK DSC enables different inverter geometries and further motor integration. The on-chip current and temperature sensors contribute to an efficient and safe inverter operation.

Rogers (**www.rogerscorp.com/pes**) demonstrated Curamik ceramic substrates designed for high-demand applications. The basis of the substrate is a ceramic isolator to which pure copper is applied. The result is ceramic substrates with high thermal conductivity, great heat capacity and heat spreading provided by the thick copper layer. These high performance substrates are well-suited for power electronics applications (see our feature "Direct Cooled Low Inductive SiC Mold Module").

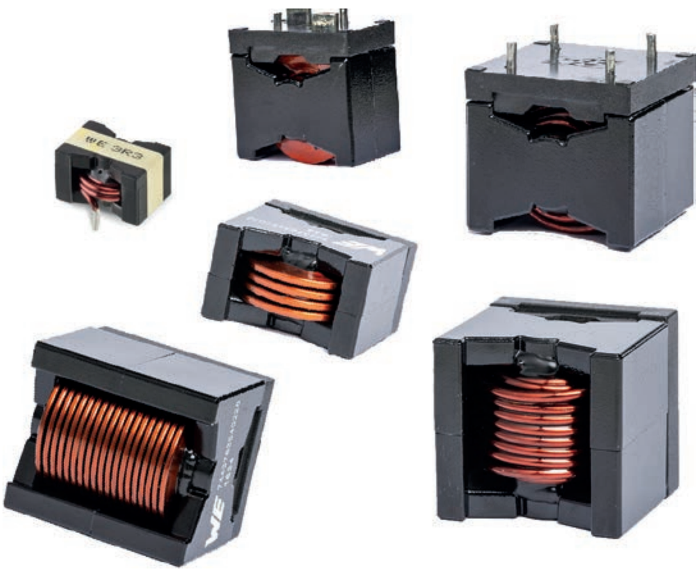
Also ROLINX customized busbar solutions and assemblies were on display, which offer low inductance, compact and highly customizable designs and in combination with capacitors, extremely low inductance and high power density capabilities.

SEMIKRON's (**www.semikron.com**) SEMITRANS 20 overcomes the limits of conventional module concepts and provides a new design approach for inverters used in applications such as traction, industrial drives and grid infrastructure. Optimised for the traction and medium-voltage market, the SEMITRANS 20 is designed as a half-bridge configuration featuring a built-in temperature sensor and opposite DC and AC power terminals. Compared to conventional modules, the stray inductance is as much as 75 % lower, providing greater operational safety and facilitating paralleling. The service life of the new SEMITRANS 20 traction module is up to 3 times longer than that of conventional traction modules. This is achieved through the use of state-of-the-art technologies such as sintered chips and AlCu Bond wires. The standardised package meets the increasing demands for lower costs, greater efficiency and durability for power electronics in industry, transportation and infrastructure.


Vincotech (**www.vincotech.com**) announced among others a unique family of high-speed power modules striking the best balance between costs and benefits. The new flowPACK 1 1200 V sixpack features tandem diode technology and a high-speed IGBT. This family of high-speed 1200 V sixpacks with tandem diodes is comprised of several IGBT modules to cover currents ranging up to 75 A at room temperature. All products ship in a flow 1 package with Press-fit pins. Every package shares the same pin-out and footprint, so drive manufacturers can easily re-use the same PCB design for various power applications. Versions with solder pins and phase-change material are available on request.



Wuerth (**www.we-online.com**) focused on high-current inductors, SMT-mountable double inductors and high-power terminals. WE-HCF and WE-HCFT high-current inductors have a current loading capacity of up to 75 A. Ferrites are WE-CBF, ideal as a data line filter and for supply voltage decoupling, and WE-MPSB, the world's first SMD ferrite series with specified peak current capability for filtering highly efficient DC/DC converters in harsh industrial environments. Over-voltage protection is addressed with WE-VD, a disk varistor that continues to operate immediately after an overvoltage pulse without sequential current. WE-MCRI is an innovative, molded double choke. The fully automatic production process with bifilar windings enables a coupling coefficient of up to 0.995. Like the WE-CFWI, it displays a soft saturation behavior which is achieved by the core material and the distributed air gap within the core. The same applies to the WE-CMBNC current-compensated line choke with its high permeability nanocrystalline core material. It is characterized by excellent broadband attenuation - with small size, high rated currents and low resistances. The robust component for the extended temperature range of up to +125°C is therefore suited for motor interference suppression and as an input and output filter for mains applications.



# Direct Cooled Low Inductive SiC Mold Module

To make use of the superior properties of wide bandgap (WBG) semiconductors, power modules are needed with optimized parasitic electromagnetic properties, a high temperature capability and the possibility for a high degree of integration. In this investigation the advantages of a new packaging method for power modules with SiC power MOSFETs on a new multilayer ceramic substrate with transfer molding technology and a direct metallized electrical layer on top surface of the package are emphasized. **Christoph Marczok, Fraunhofer IZM, Berlin; and Andreas Meyer, Rogers Germany GmbH, Eschenbach, Germany**

SiC power modules require a low inductive commutation cell with a low inductive gate path and low inductive input connectors as well as a very low thermal resistance from chip to heatsink. In this development a new approach with another highly insulating material besides prepregs is used to improve power and packaging density in power electronics.

## Module design

To achieve highest performance, the multilayer ceramic substrate (MLS, 7 in Figure 1) provides the basis of the power module. It consists of three copper layers separated by two $Si_3N_4$ ceramic layers. Compared to standard Direct Bonded copper substrates (DBCs) which provide one electrical layer and the safety insulation (7b) to the heatsink, MLS fulfills two more functions. First, its multilayer setup with through ceramic vias (7a) provides a second electrical layer (midlayer of the MLS), which allows a busbar design to realize a low inductive switching cell. Furthermore that layer is on DC+ potential and shields the switching knot/OUT potential from protected earth (PE), which reduces EMI. Second, the bottom copper contains an etched heat sink structure (7c) for direct fluid cooling.

Four prepackaged SiC power MOSFETs (8), two in parallel are sintered on the top layer of the MLS. The prepackages are electrically connected to the upper copper layer on top of the mold casing (6) with through mold vias (5).

For keeping the advantages of the low inductive module design a primary damped DC-link (2) is implemented, consisting of a resistor and capacitor in series. Furthermore low inductive power connectors DC+/- (1) to the main DC-Link and a low inductive gate path from the semiconductors to the first driver stage/booster (4) need to be considered. This aim is achieved by structuring of the upper copper layer. Therefore the booster SMD components and signal connectors (3) are soldered on the surface and the assembly plastic frame with the spring

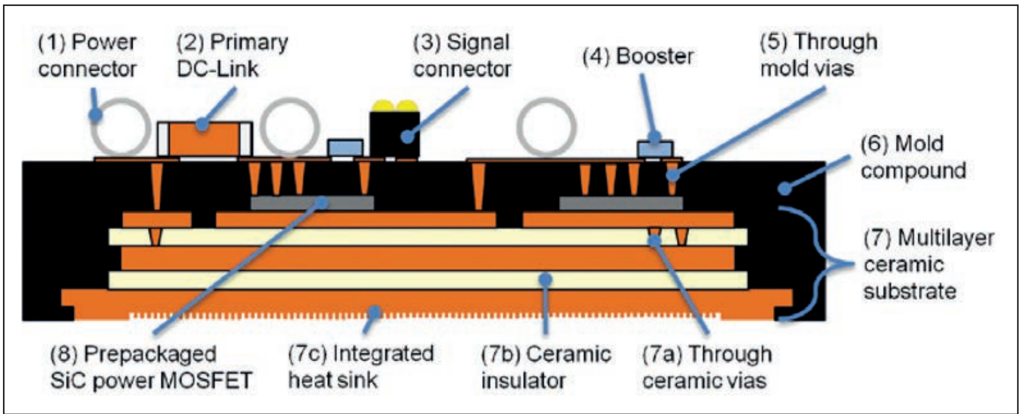



**Figure 1: Vertical layer stack of the molded power module with SMD assembly**

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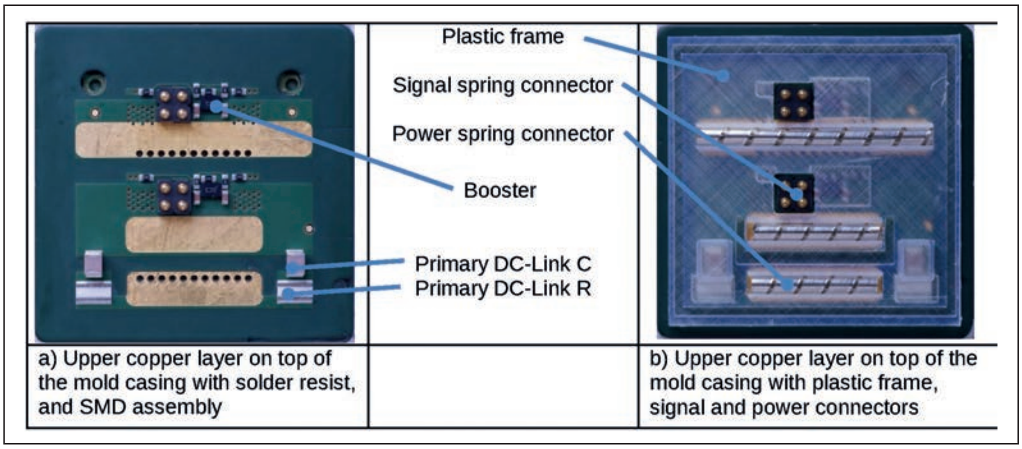



**Figure 2: Top view of the molded power module**

| Material | Thickness in µm | Thermal conductivity in W/(m*K) | Further simulation relevant parameters |
|---|---|---|---|
| MOSFET SiC | 330 | 490 | $P_{Chip}$ = 50 W |
| Ag Sintering layer | 60 | 250 | - |
| Top copper | 800 | 380 | - |
| 1st ceramic $Si_3N_4$ | 250 | 90 | - |
| Mid copper | 2000 | 380 | - |
| 2nd ceramic $Si_3N_4$ | 250 | 90 | - |
| Bottom copper | 1500 | 380 | - |
| Fluid (water) | - | | Flow rate: 6,72 l/min, Δp = 100 mbar, θ = 75 °C |

**Table 1: material parameters for the thermal simulation**

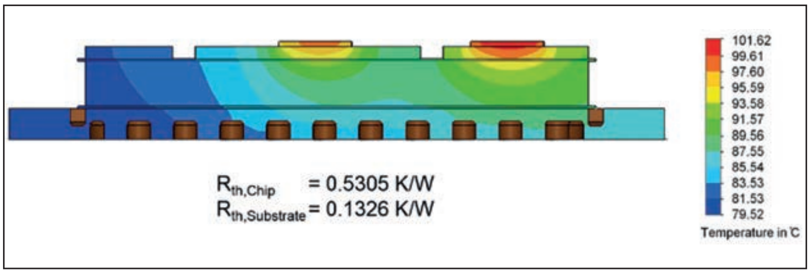



**Figure 3: Static temperature distribution in the MLS with four SiC power MOSFETs**

power connectors is attached to the power module as shown in Figure 2 a) and b).

In this developmental stage of packaging approach with a diversity of new process elements like a thick MLS with through ceramic vias, a thick substrate transfer molding process, the through mold vias and the upper copper layer on top of the mold casing a robust SiC chip reduces the development risk. Therefore the SiC power MOSFETs were embedded with a PCB process. The bottom side of the bare die is sintered to a copper foil, while the source and gate pads on top are contacted by laser drilled micro vias to the prepackage surface. Thus it was possible to expand and stretch the gate and source pad apart for a larger placing tolerance while keeping its good thermal performance. The copper thickness of the top and bottom layer is around 60 µm for a better robustness towards the through mold via process.

## Thermal analysis

The thermal analysis of the power module has been carried out using CFD simulation with SolidWorks flow simulation. The simulation model was symmetrically halved to reduce simulation time. The static temperature distribution on the designed molded power module has been investigated. Table 1 shows the material parameters and the vertical layer stack in the written sequence from top to bottom.

SiC chips are modelled as 6H-SiC, which is the type with the highest thermal conductivity. In this simulation each of all four chips generates power losses of 50 W. The thermal conductivity of the Ag sintering layer is a well experienced value for middle-low porosity. It was modelled as contact resistance with the parameters as shown in Table 1. Figure 3 shows the static temperature distribution in the MLS. The temperature difference can be calculated from the hot spot in Figure 3 on the right chip with 101.62°C and the coolant temperature with 75°C. In general power losses per chip of 188 W can be dissipated.

## Packaging technologies and manufacturing

The main manufacuring steps are shown in Figure 4. The power module is manufactured at the Fraunhofer IZM in Berlin. In Figure 4 a) the prepackaged SiC power MOSFETs are sintered on the multilayer Si3N4 substrate manufactured by Rogers in an Active Metal Brazing (AMB) process. In the next step the 4.5 mm thick MLS with a challenging filling geometry is encapsulated in a transfer molding technology, shown in Figure 4 b).

Subsequently the fiducial markings on the MLS are uncovered followed by the laser drilling process to open the 60 ?m thick copper surface of the Prepackages as well as the MLS surface. Afterwards the open surfaces are electrically connected by a sputtered copper seed layer, illustrated in Figure 4 c). In the following it is galvanized up to 60 µm and structured for the electrical functionality. In Figure 4 d) the solder resist is applied, the ENIG surface finish is made and the SMD components are placed and assembled in a reflow soldering process.

In the end the plastic frame is glued to the mold casing surface to keep the creepage distances and to keep the power spring connectors in position for DC+, DC- and OUT.

## Conclusion and further steps

An innovative power module packaging is demonstrated consisting of a multi-layer ceramic substrate with through-ceramic vias, built up in a transfer molding process and a post processing electrification of the topside of the mold casing with through-mold vias. Furthermore, a very good thermal performance was shown with a thermal resistance per chip of 0.53 K/W. Finally the outstanding electrical performance is proven with a very low commutation cell inductance of ≤ 1.6 nH.

Ongoing work will improve the power module's thermal design, its electrical interconnects, the integration of more functional, electrical elements as well as the substitution of prepackaged SiC MOSFETs with bare dies. Furthermore, the manufacturing processes will be optimized for mass production.

## Literature

*"Low inductive SiC Mold Module with direct cooling", Christoph Marczok, Young Engineer Awardee PCIM Europe 2019, Fraunhofer IZM, PCIM Europe 2019 Proceedings, pages 325 - 329*

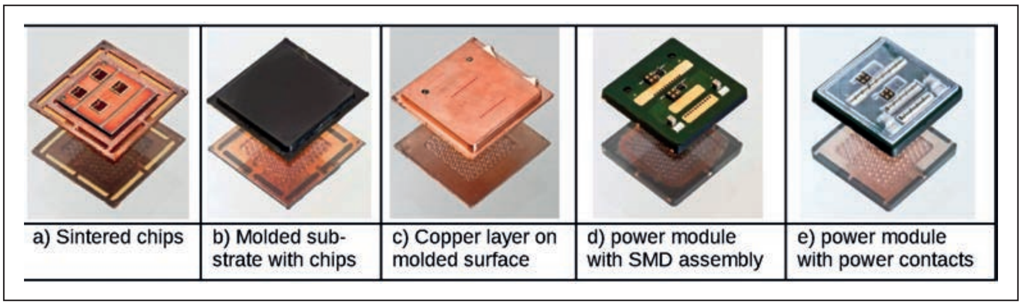



**Figure 4: Manufacturing steps of the molded power module**

# GaN Based High-Density Unregulated 48 V LLC Converters

Two-stage 48V voltage regulator module (VRM) with unregulated first stage DC/DC converter providing intermediate bus voltage followed by multi-phase buck converter has proven to be a scalable and efficient approach for 48V rack architecture in data centers. In this work an eGaN® based first stage unregulated LLC converters with integrated magnetics are proposed, the converters designed with fixed transformation ratios of 4:1 and 8:1 provide a continuous power of 900 W with maximum efficiencies of 98.4 % and 98.0 % in high-power-densities of 94 kW/liter and 75 kW/liter respectively. The bus voltage variation is evaluated to maximize the overall efficiency of 48 V VRM. **Mohamed H. Ahmed, CPES, Virginia Tech; Michael de Rooij, David Reusch, Efficient Power Conversion, El Segundo, USA**

**Significant challenges arises with 48 V** rack architecture for data centers, the 48 V voltage regulator module (VRM) in vicinity to CPU and GPU has to be designed with high-efficiency and power density.

## Single or two-stages

48 V VRM solutions can be categorized as single-stage solutions, or two-stage solutions. The first commercial available 48 V VRM from VICOR uses two-stage configuration with regulator module followed by a DC/DC transformer achieving high-efficiency and power density. The two-stage approach shown in Figure 1 was proposed with unregulated transformer based first stage converter (DCX) followed by a multi-phase buck converter, the first stage can be designed in very high-efficiency and power density while the second stage is easily scalable and low cost solution.

The same approach was later adopted by Google replacing the first stage by an unregulated resonant switched capacitor achieving very-high efficiency and power density. However, the converter requires an extra buck converter for startup and protection with special controller for operating frequency adaptive tuning to compensate for all components tolerances.

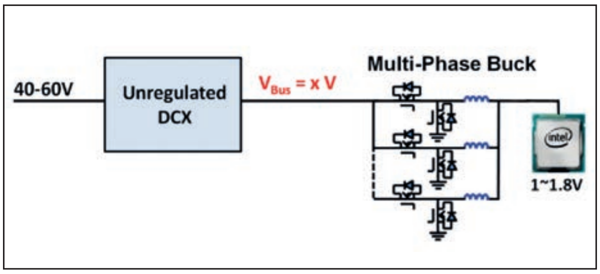
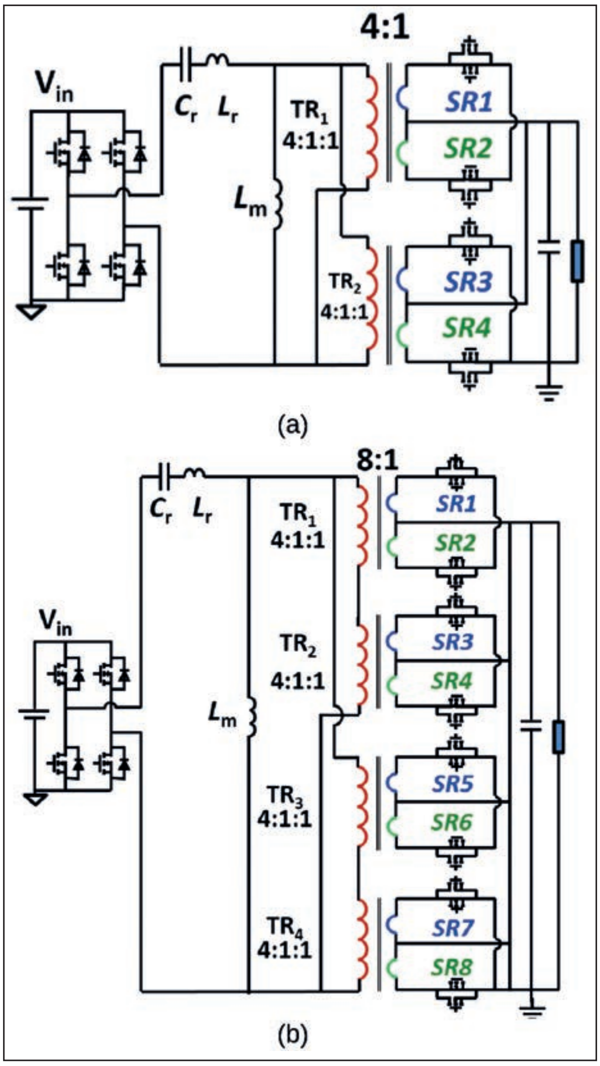
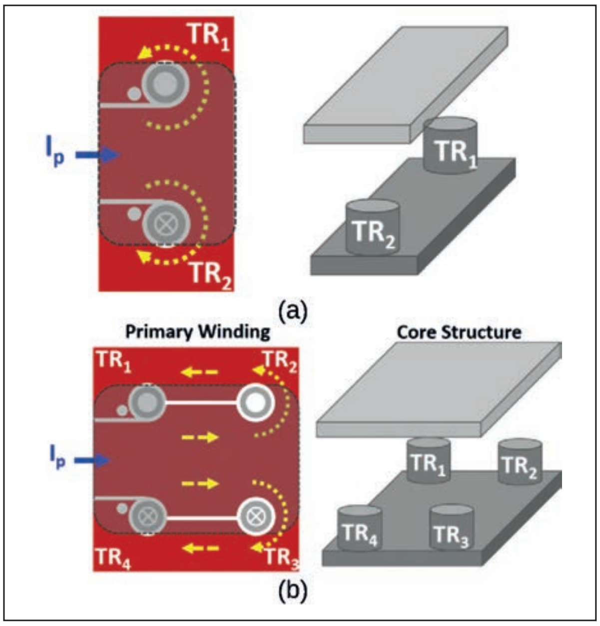



Figure 1: **Two-stage 48 V VRM solution**




RIGHT Figure 2: **LLC-DCX with matrix transformer structure (a) 4:1 LLC-DCX (b) 8:1 LLC-DCX**

In this work, the same approach is revisited. Unregulated LLC converter first stage will be used where all the startup,




LEFT Figure 3: **Symmetrical winding arrangement and magnetic core integration (a) 4:1 LLC-DCX (b) 8:1 LLC-DCX**

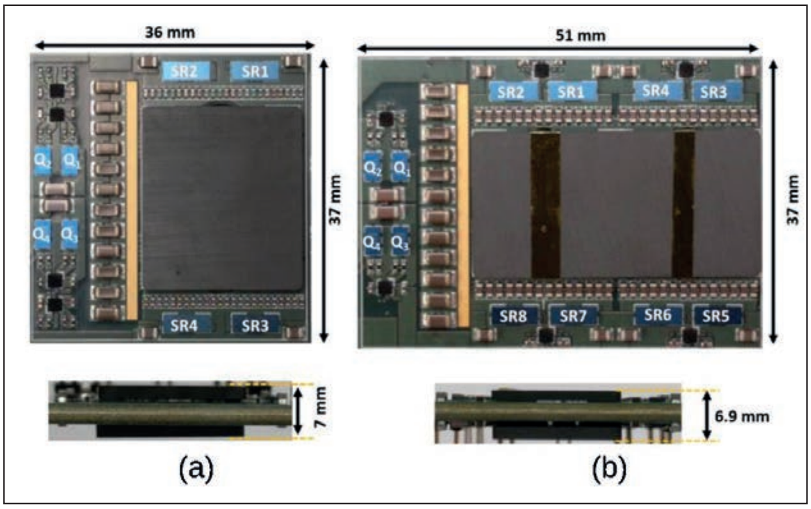



Figure 4: **48V LLC-DCX experimental prototypes (a) 4:1 LLC-DCX (b) 8:1 LLC-DCX**

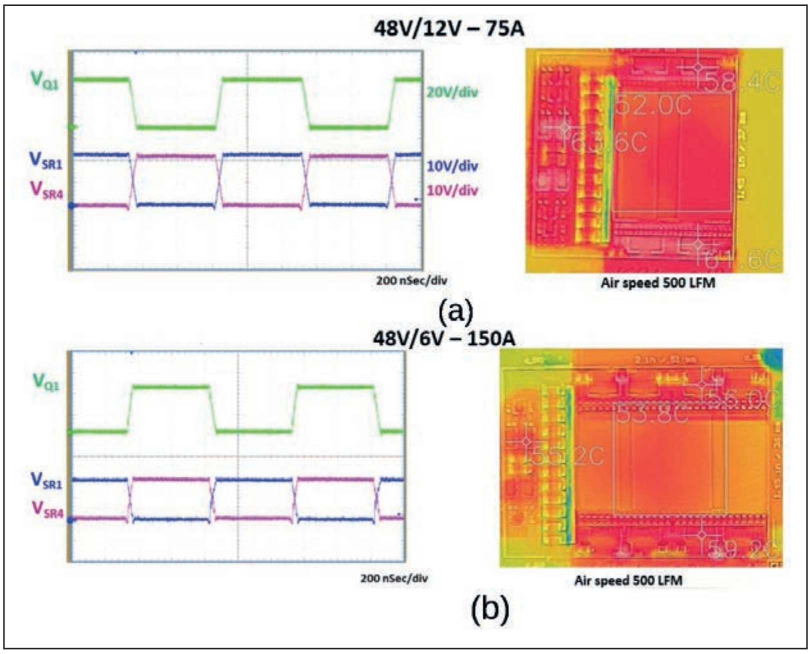



Figure 5: **Full load operating waveforms and thermal image (a) 4:1 LLC-DCX (b) 8:1 LLC-DCX**

short circuit control and synchronous rectifiers (SRs) adaptive driving can be easily implemented with a simple microcontroller. In addition, only one resonant capacitor is needed for operation no matter what is the transformation ratio of the converter. With soft switching operation for both primary and secondary devices, LLC converter designed with eGaN FETs can operate at high switching frequency (>1 MHZ) enabling high power-density with magnetic integration without scarifying efficiency.

Two GaN based LLC-DCX with integrated magnetics and fixed transformation ratio of 4:1 and 8:1 were designed for a two-stage 48 V VRM solution and the effect of the intermediate bus voltage on the two-stage efficiency will be evaluated.

## Unregulated LLC-DCX with integrated magnetics

High operating frequency LLC-DCX will be subjected to high-frequency related losses in the transformer. Matrix transformers has proven to be the best candidate for LLC transformer to avoid high-frequency related conduction and termination losses. The designed LLC-DCX with matrix transformer structure and (4:1, 8:1) conversion ratios are shown in Figure 2. With multiple secondary side windings connected in parallel, the conduction loss reduces significantly, with primary side also connected in parallel, the primary side conduction loss is reduced, to ensure equal current sharing between the two primary parallel paths, a symmetrical PCB winding while integrating the multiple elemental transformers in one magnetic core is proposed. The symmetrical primary winding for both converters is shown in Figure 3 by which equal current sharing can be achieved.

The 4:1 LLC-DCX has two-elemental transformers integrated in one core structure. The 8:1 LLC-DCX, has 4-elemental transformers integrated in a single core to deliver double the output current at lower output voltage and keep the same output power. Integrating multiple-elemental transformers in one core will help to have similar magnetizing inductance for all elemental transformers to avoid any current sharing issues between these transformers.

## Experimental results

The designed 4:1 and 8:1 LLC-DCX converter prototypes are shown in Figure 4. The primary side devices for both converters using the latest generation eGaN FET, the 100 V rated 4 mΩ EPC2053 and the secondary side devices are the 40 V rated 1.5 mΩ EPC2024 and

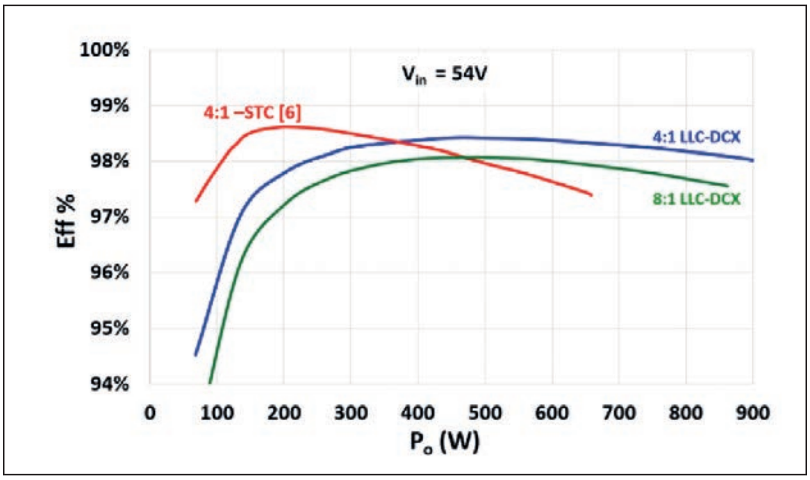



**Figure 6: LLC-DCX measured efficiency at 54 V input and comparison with state-of-art**

30 V rated 1.45 mΩ EPC2023 respectively.

The transformer magnetic core uses a custom designed ML91 from Hitachi. Both converters operate at 1 MHz and can provide a continuous power of 900 W with power density of (92 kW/liter) for the 4:1 converter and (73.5 kW/liter) for the 8:1 converter. The full load operating waveforms and thermal images are shown in Figure 5 where ZVS is achieved for both primary and secondary devices with a very good thermal performance.

The two converters demonstrated very high-efficiency operation ≥ 98 % that is a percent higher and with higher power-density than a comparable state-of-art solution using STC as shown in Figure 6.

## Summary

In this paper an optimized integrated magnetic structure is proposed for a first-stage LLC converter in a two-stage 48 V VRM solution for data center applications. The designed converters with GaN devices and an optimized integrated magnetic structure can achieve very high efficiency of 98.4 % for (4:1) conversion and 98.0 % for (8:1) conversion with very high-power density of (98 kW/Liter) and (74 kW/Liter), respectively. The two-stage VRM efficiency was evaluated with different bus voltages, and 6 V was selected as an optimal intermediate bus voltage.

## Literature

*"GaN Based High-Density Unregulated 48 V to x V LLC Converters with ≥ 98% Efficiency for Future Data Centers", Mohamed H. Ahmed, Young Engineer Awardee PCIM Europe 2019, Center for Power Electronics Systems (CPES), The Bradley Department of Electrical and Computer Engineering, Virginia Tech, USA; PCIM Europe 2019 Proceedings, pages 69 - 76*

# Power GaN Can Revolutionize the Industrial World

Industry 4.0 brings rise to an era of smart factory floors that synergize mass production capabilities with automation, robotics, and M2M communication. Modern factories and industrial spaces must be increasingly intelligent and efficient with capital, costs, and energy, whether it's for pharmaceuticals, chemical, transportation, medical devices or fulfillment centers. However, power system design is reaching the theoretical limits of Silicon-based power devices. With its smaller, more energy-efficient and cost-effective capabilities, gallium nitride (GaN) plays a leading role in Industry 4.0. **Paul Wiener, VP Strategic Marketing, GaN Systems, Ottawa, Canada**

Two major application areas in the next industrial revolution are motors/motor drives and robotics/robots. GaN-based design and technical features in these areas keep factories competitive, flexible, efficient and optimized as we meet growing customer demands.

## Motors and drives

Motors and the motor drives that harness and control industrial motion are the hidden workhorses of Industry 4.0. They are embedded in a variety of applications, including robotics, storage and retrieval shuttles, bulk conveying, packaging machines and fabrication systems. In robotics, servo motors in every joint of a robot are used to actuate movements, enabling precise angles in a robot arm. On conveyor belts, servo motors move, stop, and start products along various stages of an assembly line, such as for packaging and labeling. In fabrication, metal cutting, and metal forming machines, servo motors provide precise motion control for milling machines, lathes, grinding, centering, punching, pressing, and bending metal – from jar lids to automotive wheels.

With such a variety of applications, motor and motor drives are challenged with energy efficiency and design flexibility. The stakes are global: industrial markets account for 40-50 % of electricity used in the world, with motors using two-thirds of that. Today, there are 300 million motors in the industrial segment with 10 % annual growth. Insulated Gate Bipolar Transistor (IGBT) motors drives are not highly efficient when it comes to power conversion and use, with up to 30 % energy loss. GaN addresses this challenge.

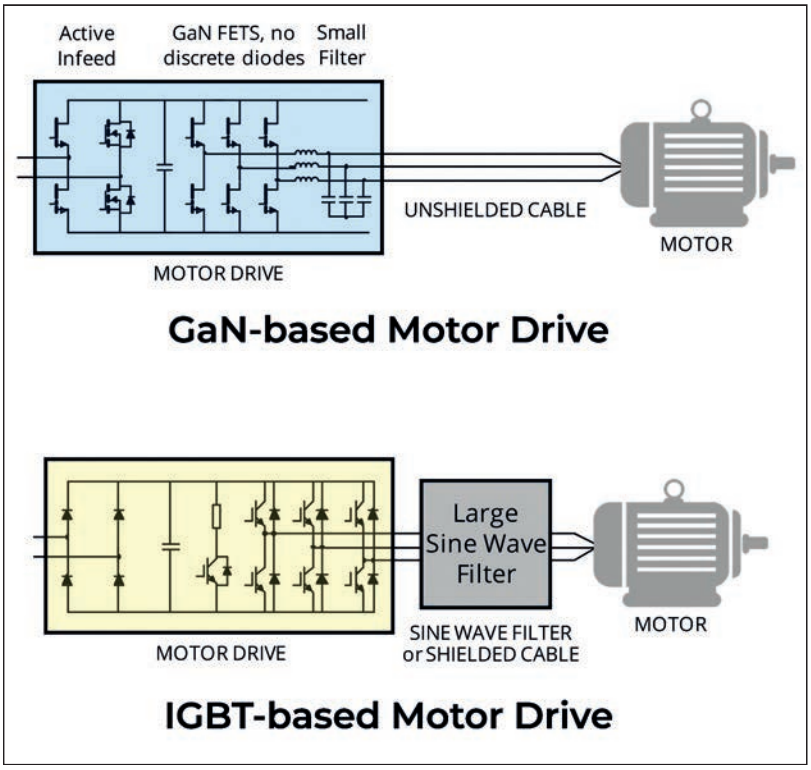



**Figure 1: GaN-based and IGBT-based motor drive schematics**

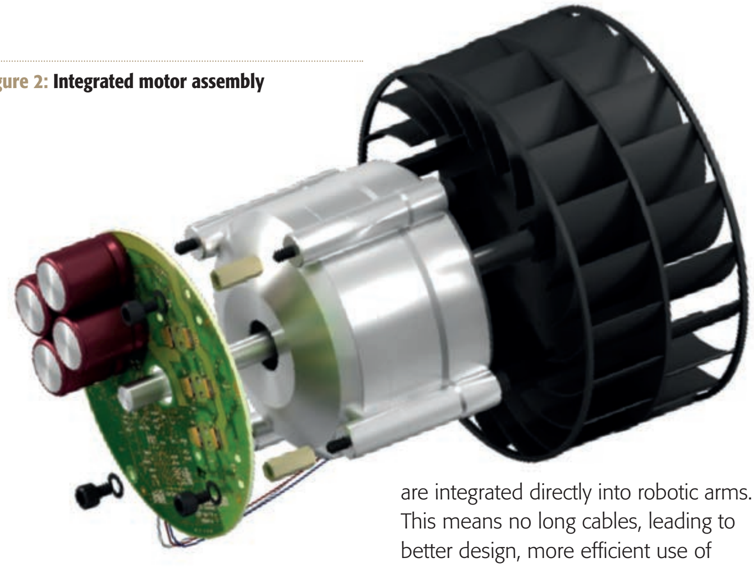
## GaN-based versus IGBT-based motor drives

One of the advantages GaN has over IGBTs in this applications is that the motor drive can be up to two times smaller because of lower losses. Efficient higher switching frequency offers savings in costs and cabinet space. These features mean the drive module can fit an active infeed and LC filters, as highlighted in Figure 1a. The active infeed allows for smaller, cheaper filters and no braking chopper while meeting harmonics requirements with regeneration. There are also the advantages of no acoustic noise, built-in sinusoidal output filter, and increased system efficiency of 98 % (versus 92 % with IGBTs). These features lead to quieter operating environments, smaller size, lower operating costs, and the ability to use long, unshielded cables. These cables offer more flexibility and lower costs while increasing the motor lifetime and having an easy-to-use inverter.

Drive size is further reduced because GaN does not require additional SiC freewheeling diodes, as shown in Figure 1b. GaN drives have heatsinks that are 40-70 % smaller – or there is no heatsink at all – with two times more power density. Altogether, GaN offers 40-60 % smaller devices and 10-20 % lower costs.

An example of design flexibility in practice is demonstrated in an integrated motor assembly design (Figure 2). This

Figure 2: **Integrated motor assembly**



assembly has voltage and current feedback for each of the three-motor phase control half bridges, up to 1.5 kW at 300 V, and five times the power density of existing 12 V BLDC motor controllers. The elegance of this design lies in a motor assembly that creates one motor controller for all voltages and a simple interface of power, communication, and ground. This is a low-cost universal design that is part of the future of motor drives.

## Robots and robotics

GaN power transistors advance robot and robotic performance in three important areas: size, precision, and autonomy. Today, power conversion and motor drive components of robotic arms can be so large that they are located in separate cabinets distant from the arm on the assembly line. This requires expensive cables and sub-optimal layout. GaN's size and power conversion efficiency enables motor drives and power conversion that are integrated directly into robotic arms. This means no long cables, leading to better design, more efficient use of facilities, and, ultimately, lower operating costs.

With Industry 4.0, there is a growing need for more complex robotics with multiple motors working simultaneously in an orchestrated and controlled manner. In all industrial applications, precision, flexibility, dexterity, and speed are critical; whether it's for small parts assembly, part transfer, part presentation, dispensing, or packaging. GaN-based power systems address these next generation requirements. Multiple motors working simultaneously require improvements in motor drive control. GaN-powered semiconductors in robotics increases the motor control precision by reducing or eliminating mechanical vibration. Furthermore, GaN enables hardware switching with a figure of merit (FOM) that is 10-13 times better than today's Silicon MOSFETs. Motor drives operating at higher frequencies and efficiencies deliver increased control bandwidth for the motor.

The business operating results are 1) faster response times from incident detection to action and 2) higher real-time precision positioning and control with extensive degrees of freedom and dexterity, as illustrated in Figure 3.

## Autonomy and wireless charging

In current industrial environments, humans work with robots to control the processes and optimize decision-making. However, robots are becoming increasingly autonomous and mobile. When we consider how we get to true robotic autonomy, wireless charging is a significant part of the answer, as depicted in Figure 4.

For wireless power transfer (WPT), GaN again has an significantly advantage over Silicon-based solutions. GaN-based power systems result in higher power transfer capabilities of up to 1 kW versus 15 W with Silicon, and device spatial freedom in X, Y and Z axes that enables air gaps up to 200 mm between power transmitter and receiver. This means that devices can operate in harsh conditions with enhanced durability and maximum robot uptime. The problem with contact-based charging is that exposure to dust, moisture, and other debris negatively impacts performance and requires expensive maintenance. Wired power equipment is prone to failure and physical wear-and-tear, causing expensive robot downtime. With no power connectors to worry about, wireless charging systems can be sealed against dirty and corrosive environments. This makes operations possible in environments where wires are not possible or are unsafe, such as in mining or underwater operations. Having reliable power to wireless robots with high power levels and high degrees of positional flexibility optimizes productivity on a continuous self-charging cycle that never wears out.

Automated Guided Vehicle Systems

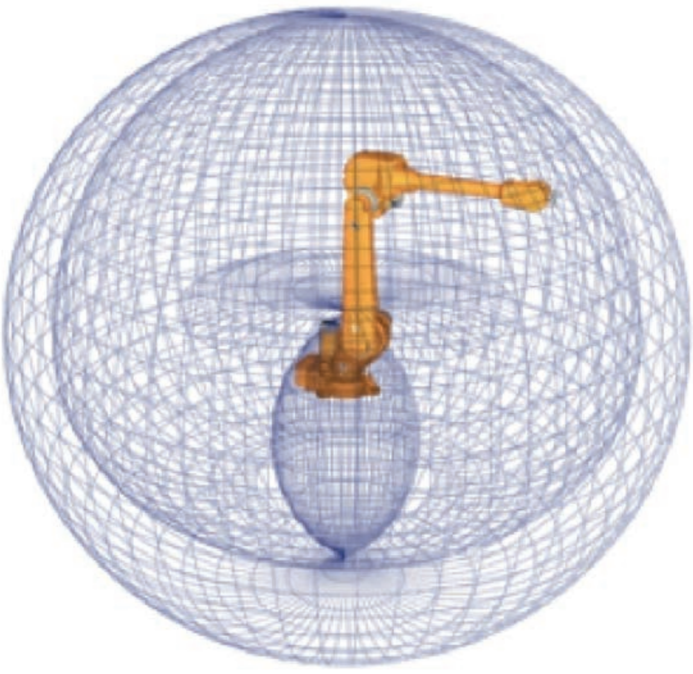


Figure 3: **Precision and performance are significantly enhanced with GaN-based drives**

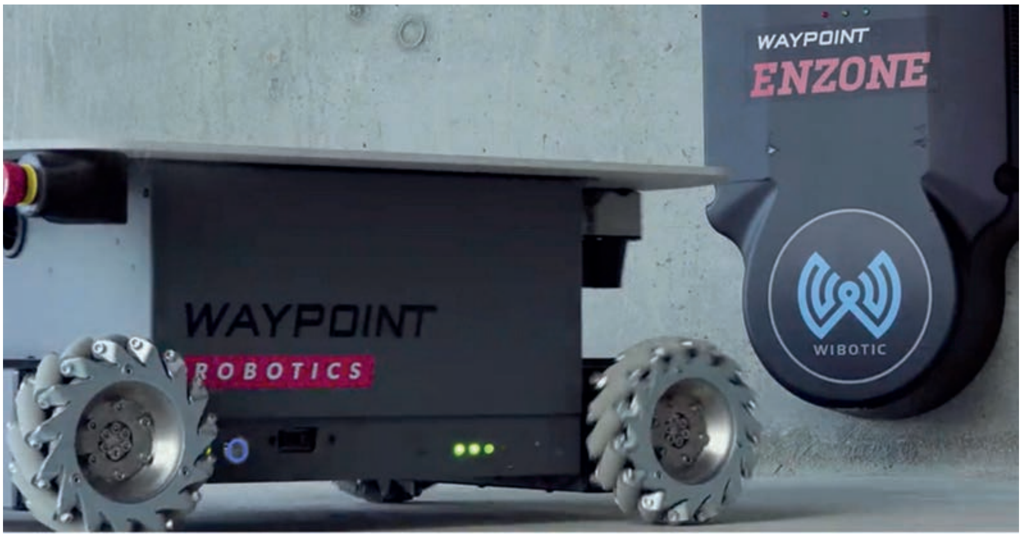



**Figure 4: Wireless power transfer in robotics enables high autonomy**

(AGVS) are an example. AGVS's follow guided paths and have robotic arms that perform repetitive and precise tasks on assembly lines. To charge the vehicle in a wired environment, a human operator makes a physical connection with a docking mechanism. In a wireless environment, the vehicle parks itself over a charging pad, eliminating human intervention. Inefficiencies are mitigated further with no docking mechanisms, no failure-prone wiring and connectors, and no labor-intensive manual recharging. Finally, with such a low profile, wireless charging stations can be placed throughout a facility to provide "opportunity charging" for maximum robot uptime. Wireless charging allows mobile robots/AGVS to work efficiently and without interruption.

## Conclusion

Industrial, governmental, and environmental pressures are changing how we make, move and package products. We operate in a world with hundreds of millions of motors, motor drives, robotics and robots that continuously require innovation to improve performance. With GaN, system designers have the ability to change motor drive design to be smaller and more energy efficient, robotics to have high precision, and enable true autonomy for robots. All of these actions will have an exponential impact on the revenue and environmental metrics of Industry 4.0.

# High-Power Module Platform for Automotive Traction Applications

A paper on a novel power semiconductor module platform for the automotive powertrain was awarded as the best PCIM 2019 paper. Here mold modules are designed for symmetric and minimized parasitics by applying alternating and multilayer current routing. All interconnects are solder-free to provide superior reliability, and to meet present and future automotive requirements, e.g., passing 1000 temperature shock cycles in the range of -40 to 150°C. SiC or Si devices are packaged in the same external outline offering scalability for inverter classes in the 150 – 350 kW power range. A screw-less and O-ring-less 3-phase inverter module is achieved by a laser welding of the mold modules to a low-cost Al cooler enclosure. **Jürgen Schuderer, ABB Corporate Research, Switzerland; and Andreas Apelsmeier, AUDI AG, Germany**

**The recent electric vehicle (EV) outlook** from the International Energy Agency projects a rapid growth of global vehicle stock from 3 million vehicles in 2017 up to 228 million electric vehicles by 2030. This tremendous growth will come along with the need for cost-effective and reliable power electronics inverters within the electric powertrain of hybrid, plug-in hybrid, and battery-electric passenger vehicles, as well as light-commercial vehicles, buses, and trucks. At the heart of the inverter are power semiconductor devices arranged in multi-chip power modules that control the motor torque and speed via pulse width modulation (PWM).

Power modules must be optimized for mechanical integration into highly compact inverters that are mounted in space-restricted engine compartments of Evs. Strategies for power module footprint reduction are the expansion of current routing into the third dimension, the improvement of the cooling path to reduce chip area, and the high-temperature operation of wide-bandgap (WBG) semiconductors to extract more power from the same outline. This goes along with the trend to integrate the power inverter with the electric motor into a single unit to eliminate interfaces and make use of common infrastructure (structural, cooling, busbars).

Thus it is expected that the automotive market dominance will significantly drive innovation and lead to accelerated implementation of new materials and manufacturing methods, which need to be carefully assessed with respect to reliability issues. Examples are the deployment of fast-switching WBG devices, application of new bonding technologies like planar topside bonding, sintering, PCB embedding, and the heterogenous integration of passives, diagnostics sensors, drivers, transceivers, and other on-board components. Finally, commercial vehicles like buses and trucks are designed for longer lifetime than passenger EVs, e.g., 60,000 vs. 7,000 hours, and the resulting increased reliability demands need to be considered.

## Power module design concept

A SiC / Si power module platform was developed to address automotive performance requirements (Figure 1) .

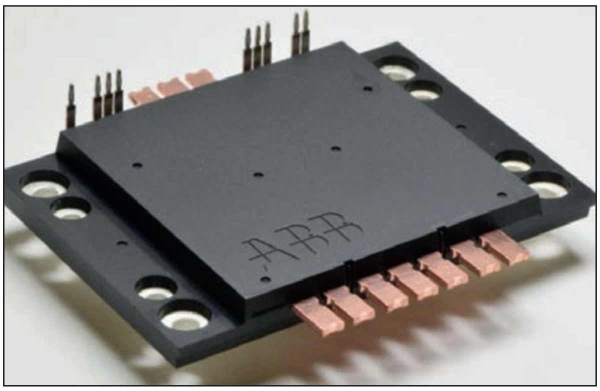



**Figure 1: 900 V SiC mold module, Gen 1 design**

To address the cost issue, a mold module approach has been selected that does not require any housing. The mold encapsulation provides 1) good environmental protection by low moisture absorption and water vapor diffusion, 2) good cycle reliability by its hard-mold, compressive and low-coefficient of thermal expansion (CTE) encapsulation, and 3) excellent protection against shock, vibration and handling damage.

A completely solder-free power module is realized for the highest cycle reliability and robustness standards. All interconnections are either sintered or welded. Furthermore, this approach allows for a superior manufacturing throughput, because the sintering of all power module components can be realized in a single process step.

To allow for SiC fast switching, power loop and gate loop inductances as well as coupling coefficients are rigorously minimized. This is achieved by applying a systematic alternating (+/-/+) signal routing of power- and gate circuitry to substrate and terminals, and by using multilayer signal distribution inside the module.

A low-cost cooler enclosure is realized by laser welding of mold modules into a structure based on cheap embossed Al sheets. In this manner, a compact 3-phase inverter module is achieved without the need for screwing or clamping of O-ring sealings that could pose a risk of leakage.

The proposed power module offers several aspects of scaling. First, two different substrates are applied to assemble either a high-power SiC, or a

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lower-power Si version for the identical external outline. Second, due to a special symmetric substrate layout, further power scaling is possible by adding or removing chips along the length of the module (x-direction in Figure 2) without impacting stray inductances and coupling coefficients. Finally, module cost can be scaled by applying different power module component materials (substrates, baseplates, bond materials) to optimize for the right cost-performance ratio for the specific target vehicle.

## Half-bridge module design

The mold modules are designed in half-bridge configuration. Two different types were developed, a 900 V SiC version for screw attachment to the cooler, referred as Generation 1 (Gen 1), and a 1200 V SiC and Si version for direct cooler bonding, referred as Generation 2 (Gen 2), see Figure 2. Both types were designed using similar packaging technologies and materials.

A CTE-matched pin-fin baseplate made from AlSiC with a pin-field optimized for maximum heat transfer and small temperature differences between parallel chips is applied to support a homogeneous current sharing. A main ceramic substrate made from $Si_3N_4$ is bonded to the baseplate by Ag-sintering. Semiconductor dies, NTC temperature sensor and external per-chip gate resistors (only SiC version) are Ag-sintered to the main substrate. Top plates made from Cu are Ag-sintered to the power semiconductor chip top surface to enable high-reliability Cu source wire bonds. Al is used for the remaining bond wires (gate, auxiliary source, substrate-to-substrate bonds), see Figure 3. $Al_2O_3$ second-level substrates are Ag-sintered to the main substrate and used for low-inductance current routing of the control signals. Cu power terminals and auxiliary terminals with press-fit pins are bonded to the main substrate by ultrasonic welding, see Figure 4.

The module is encapsulated by an epoxy-based transfer mold material with optimized CTE. A screw thread is embedded in the mold compound that allows tight fixation of the gate driver board and alignment of the modules during assembly on the cooler enclosure. The substrate and terminal design is optimized to achieve symmetric and minimized stray inductances and cross-coupling. This is achieved by the following design approaches, see Figure 5.

The DC commutation loop and the gate loops of the half-bridge module are arranged in an alternating design so that the magnetic fields cancel out to a large extent. In addition, a control signal distribution on second level substrates reduces the cross-coupling from the power into the control loop.

Beside the small commutation loop inductances, it is a desired feature of the given designs that gate inductances and mutual inductances are small and symmetric across parallel chips allowing for fast and balanced switching. A simulation of the per-chip switching transients for the SiC Gen 2 module is shown in Figure 6. Note that the data indicates a small difference of chips 1 - 4 vs. 5 - 8. This comes from the die arrangement in two rows leading to slightly different coupling and gate inductances.

## Packaging technologies

SiC and Si chips were sintered on $Si_3N_4$ ceramic substrates with Ag or NiAu surface plating (nano-particle based Ag materials sintered at pressures ranging from 10 to 20 Mpa and temperatures around 250°C). A pick & place tacking process was used for accurate alignment, and chips and top plates were sintered in a single step. Thermal shock cycling tests between -40°C


**Figure 2:** 1200 V SiC and Si mold module, Gen 2 design

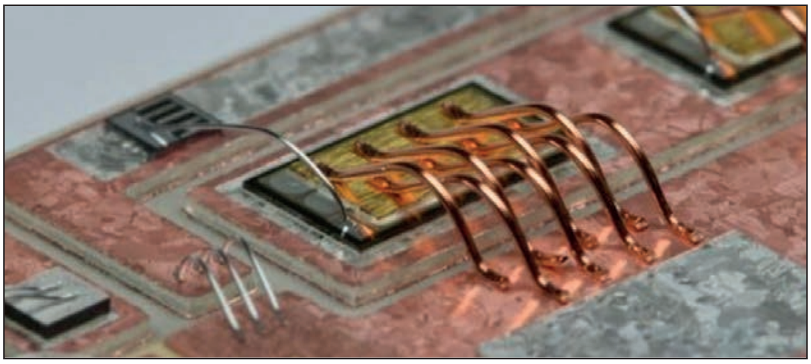

**Figure 3:** Cu source wire bonding on top plate; Al wire bonding for gate, auxiliary source (not shown), NTC (bottom left) and interconnects on substrate

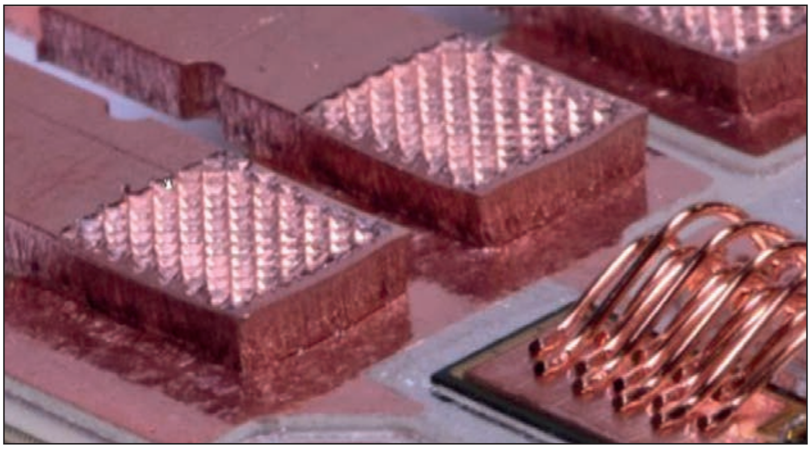

**Figure 4:** Ultrasonic welded leadframe terminals

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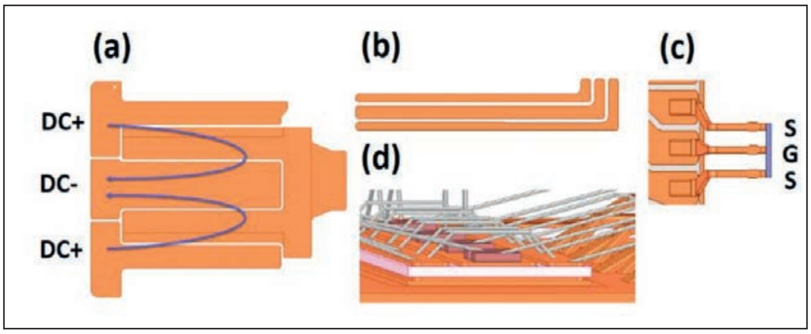


Figure 5: **Alternating current routing for DC+ / DC- current path (a); (b) and (c) Kelvin source and alternating control signal routing on substrate and terminals; (d) Multilayer signals on second level substrate for minimal magnetic coupling into the gate - source control loop**

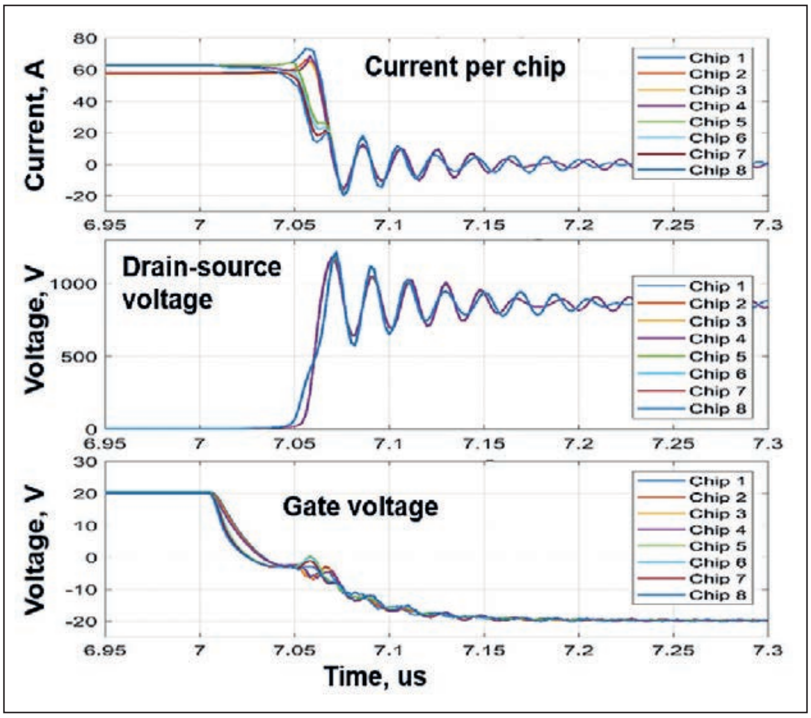


Figure 6: **Simulated switching waveforms for turn-off event based on parasitics extracted at 100 MHz; high-side chips of Gen 2 SiC module are plotted**

to 150°C with a dwell time of 5 minutes at each temperature were conducted to verify the sinter bond quality. After regular intervals of cycles, the samples were inspected using scanning acoustic microscopy (SAM) to detect any delamination or degradation of the bond layers.

It is well known that apart from the die attach, the chip topside interconnection is a main limiting factor for the lifetime of power semiconductor devices in active load cycling conditions. To improve this issue, sintering a top plate on devices with standard Al metallization and NiAu plating was performed. The top plate acts as a buffer and allows for Cu wire source bonding with superior power cycling lifetime. Different materials (Cu, Mo) and thicknesses (50 μm, 70 μm, 100 μm, 150 μm, 200 μm) have been tested. As a conclusion, a top plate made of Cu or Mo in the thickness range of 50 – 100 μm showed the best reliability in thermal shock cycling.

Heavy Cu wire bonding has been proven to be a superior alternative to Al wire bonding with greatly improved power cycling lifetimes (due to the higher electrical and thermal conductivities and greater mechanical strength of Cu). However, the process comes with some challenges such as high bond forces, narrow process window, influence of top plate material, thickness and surface properties, as well as accelerated tool wear. Thus a 300 μm Cu wire bonding process was optimized by pull and shear testing. A special focus was dedicated to identify the best compromise for the bond force to avoid cratering and chip topside damaging (gate-source short), and to achieve sufficiently high shear forces. As a result: whereas Al wire bond reference modules failed at around 20,000 cycles, the sintered top plate and Cu wire bonded modules were able to reach more than 1,000,000 cycles without failure.

Among the different ceramic substrate materials commonly used for high-power semiconductor modules, Al/AlN DBA and Cu/Si3N4 AMB substrates have been reported to achieve the highest thermal cycling capabilities. Since Al metallization can be problematic for the ultrasonic welding of Cu terminals, a Si3N4 AMB substrate was selected. In addition, to achieve highest-level reliability when targeting high-temperature operation of SiC, a substrate sintering process has been developed.

Different baseplate materials (Al, Cu, AlSiC), different bond line thicknesses (20 and 40 μm) and different sinter materials (Ag film, Ag preform with metal core) were tested by thermal shock cycling. It turned out that the metal-core sinter preform and an AlSiC baseplate provide best reliability performance. Virtually no delamination of the substrate-to-baseplate attach was found after 1,000 thermal shock cycles both from −40°C to 150°C and from −5°C to 200°C, as well as high-temperature storage tests for 1,000 hours at 200°C and 225°C.

## Three-phase inverter module and cooler design

Water-glycol cooling of power semiconductor modules by means of pin fins has become a preferred way in the thermal management of traction inverters of EVs. Pin fins are either integrated in the module's baseplate for direct cooling, or are part of a separate, closed cooler, to which the modules are attached. Whereas the Gen 1 module was designed for screw attach and sealing by an O-ring, the Gen 2 module has the full cooler metallurgically bonded to the mold modules.

The cooler assembly concept and final inverter module with cooler are shown in Figure 7. The cooler consists of three basic parts: an Al frame plate that is laser-welded to the mold modules in a first step, an Al cover plate that is welded to the frame in a second step, and fluid ports that are welded to the cover in a final step.

A critical bonding process is the welding of the cooler frame to the mold module baseplates. Heat input during this welding step must be minimized to avoid thermal damaging of the modules. Due to this reason, laser welding has been chosen since it is an exceptionally fast process, limiting the temperature rise at the mold compound side of the power module to less than 200°C. Careful process optimization and well-designed jigs are required to achieve a fluid-tight joint with

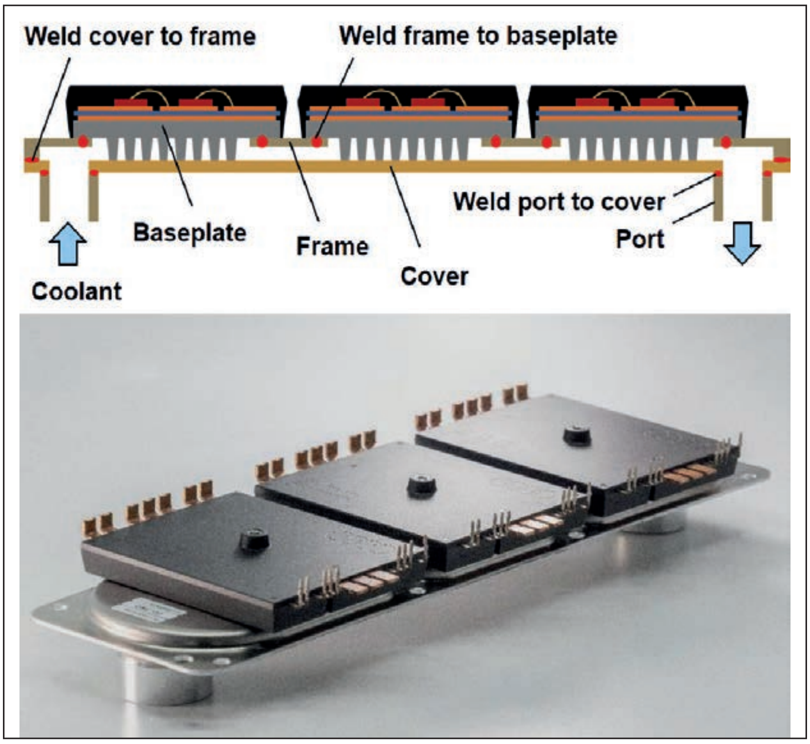


Figure 7: **Cooler schematics and 3-phase power module**

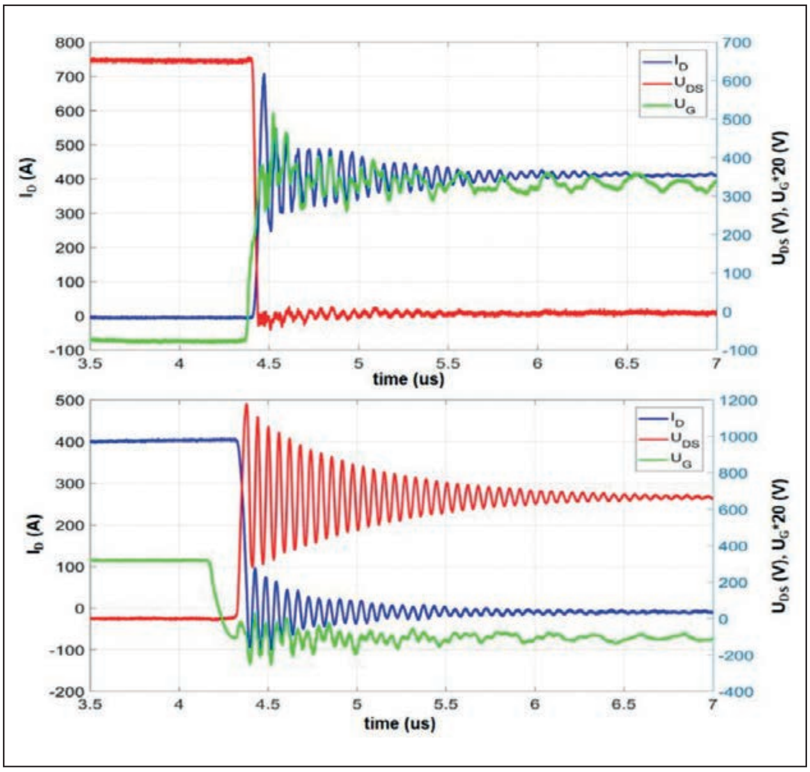


Figure 8: **Turn-on (top) and turn-off (bottom) switching waveforms of SiC Gen 2 module at 25°C; blue: current, red: voltage, green: gate voltage**

| Module type | $R_G$ [Ω] | $E_{on}$ [mJ] | $E_{off}$ [mJ] | $E_{rr}$ [mJ] |
|---|---|---|---|---|
| SiC Gen 2 | 1.7 | 17.8 | 6.9 | - |
| SiC Gen 2 | 0.0 | 1.4 | 10.8 | - |
| Si Gen 2 | 0.0 | 23.9 | 71.1 | 50.1 |
| SiC Gen 1 | 1.3 | 3.7 | 4.1 | - |

LEFT Table 1: **Switching losses measured by double-pulse testing; Gen 2: U = 800 V, I = 400 A, Gen 1: U = 400 V, I = 400 A; T = 100 - 150 °C; RG = total chip-external gate resistance**

high process repeatability. As an example, material cracks within the welded bond lines may occur that can lead to coolant leakage.

## Switching losses and rating

Double-pulse testing was conducted to determine the switching losses and to assess the power rating to the different module variants. Tests were performed in the temperature range from −20 to 150°C at DC-link voltages up to 850 V, and for currents up to 600 A. Switching waveforms for a Gen 2 SiC hard switching are shown in Figure 8.

The measurement was done at a DC-link voltage of 650 V, a current of 400 A, a temperature of 150°C, zero gate resistance (hard switching) and for a stray inductance of the test setup of about 30 nH. Pronounced oscillations results from the fast switching combined with the high stray inductance of the tester. It is therefore important to operate the module in a low inductive inverter environment for optimal performance. In general, however, the traces are quite clean. This is especially important for the critical gate voltage trace (to avoid parasitic turn-on and other issues).

Switching losses as measured by double-pulse testing are reported in Table 1. SiC losses are given for a gate resistance of 1.7 Ω, and for a hard-switched configuration with 0 Ω. In addition, Gen 2 Si losses and Gen 1 SiC losses (at a DC-link of 400 V) are given. Note that tests were performed with different double-pulse setups and gate drivers which makes a direct comparison difficult.

## Conclusions

An automotive SiC and Si power module platform targeting inverter classes of premium and commercial EVs in the power range of 150 – 350 kW was presented. Mold modules are bonded to an integrated cooler enclosure that allows for a compact, and screw-less inverter design. High-reliability packaging technologies are employed enabling operation up to 200°C junction temperature.

## Literature

*"High-Power SiC and Si Module Platform for Automotive Traction Inverter", Jürgen Schuderer, BPA Winner, ABB Corporate Research, Switzerland, and Andreas Apelsmeier, AUDI AG, Germany, PCIM Europe 2019 Proceedings*

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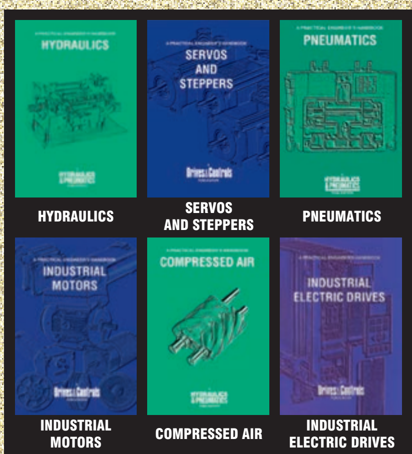


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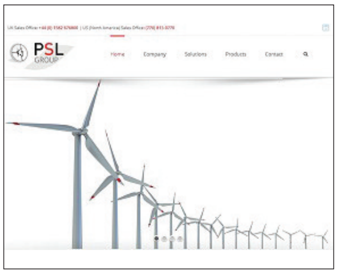

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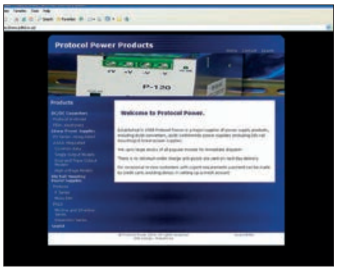

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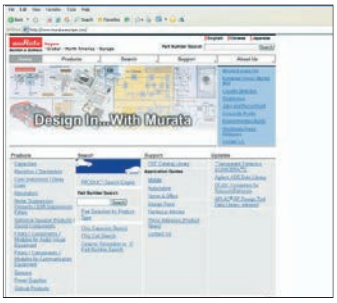

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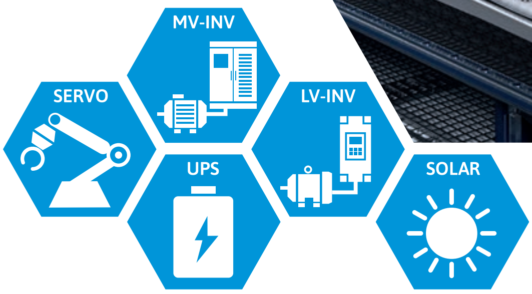


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