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## AUTOMOTIVE POWER

## Design Considerations for fast DC Chargers Targeting 350 Kilowatt


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### Also inside this issue

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## COVER STORY


## Design Considerations for fast DC Chargers Targeting 350 Kilowatt

Fast charging refuelling points will require dedicated electrical low or medium voltage (LV/MV) infrastructure as their supply. It is expected that this will be installed primarily in locations such as motorway service stations along key routes between cities. The incoming AC supply feeds into an isolating transformer whose secondary will be converted to DC. Transformers with a double secondary ∅ and Y winding are a popular solution. These phase-shifting transformers are then combined with multi-pulse rectifiers operating in series or parallel that reduce harmonic content at the input. In such designs the transformer is mandatory even if isolation can be provided through the chosen topology for the DC/DC stage, mainly due to the harmonic content improvement its presence provides. The first design decision to be made here is whether to take a common AC or common DC bus approach. Workings groups within standards organisations have, around the world, defined everything from the operational envelope and charging sequence, to the communication and connectors of High Power Chargers (HPC). In Europe and the US interested parties have coalesced around CharIN and the Combined Charging System (CCS). Elsewhere other alternatives have developed, such as CHAdeMO in Japan and GB/T in China. Some vehicle manufacturers have also placed value on developing proprietary charging solutions. For manufacturers looking to address this market it quickly becomes clear that a modular approach is required. The article shows how to proceed in this way. More details on page 33.

Cover image provided by Infineon Technologies, Germany.

# WBG Power Semiconductors Accelerate Worldwide Competition in Key Markets

The Applied Power Electronics Conference 2019 in Anaheim/California was setting a land mark for the power electronics community early this year. The event attracted more than 6,600 delegates compared to the 5,500 in 2018. This success story is largely due to the fact that power electronics are getting more importance in our daily life not only in powering our electric or electronic devices, but also industrial automation (Industry 4.0), transportation (EV/HEV/traction) or IT (cloud computing/datacenters). For all these applications active power devices such as transistors (Si/SiC/GaN), power modules and passive components (capacitors/inductors) play a vital role.

New semiconductor-based materials at device level - such as SiC or GaN - are intrinsically advantageous compared to Silicon due to their higher band gaps, lower conduction losses, and higher electron mobility. Both SiC and GaN expect to benefit from the arrival of EV/HEV with an increase in production, and to finally have a significant entry into the power semiconductor industry. Market researcher Yole expects the SiC market for EV/HEV will reach about $400 million by 2022. Overall Yole predicts a $1.5 billion market in 2023, with a 31 % CAGR between 2017 and 2023.

The third generation of semiconductors, including SiC and GaN, use materials such as other nitride semiconductors, oxide semiconductors, and diamonds, expressed Professor Yu Hongyu from Shenzhen's Third-Generation Semiconductor Research Institute in an interview with SUSTech. They have high physical characteristics such as high electric fields, thermal conductivity, electron saturation drift rate or radiation resistance. It is the core material and key component of next-generation power electronics, radio frequency, and optoelectronic applications. More than these, it can effectively support new energy vehicles, rail transit and green energy. Key applications for third-generation semiconductors include new energy and smart grid, rail and new energy vehicles, 5G communications and the Internet of Things. There are a wide range of social impacts. Firstly, the power devices and modules of the third-generation semiconductor materials can greatly reduce the energy loss and complexity of the power system and are applied to smart grids, high-speed rail transit, and new energy vehicles. Energy-consuming applications such as industrial motors, white goods, and data centers will create considerable energy-saving space and meet the global development needs of green-oriented, low-carbon development. Secondly, the future of 5G mobile communications, massive device connections, emerging new services and new application scenarios put high demands on ultra-high traffic density, connection density, and mobility. The third-generation semiconductor technology can meet the development needs of the information-based society of building an autonomous and controllable Internet of Everything and Mobile Internet. Thirdly, the development of the third-generation semiconductor industry can help traditional industries develop and upgrade. For example, Micro LED is expected to break through South Korea's dominant position in the display field and promote China's comprehensive industrial upgrade. **The development of the third-generation semiconductor industry is also expected to break through the leading position of developed countries in the field of automobile manufacturing**. Fourthly, the third-generation semiconductor power devices using high-frequency, high-reliability, long-life, wide operating temperature range, and strong anti-irradiation capability also have positive significance for the construction of defence weapons. Thus western economies should take care to keep up with such emerging competition!

According to Yole, as from 2017, Chinese automaker BYD uses SiC MOSFETs in some of their on-board chargers and certainly later in drive inverters, other car manufacturers expect to have their first SiC-based module prototypes running as from 2020. Regarding GaN, LiDAR (Light Detection and Ranging) applications are high-end solutions that take full benefit of high-frequency switching capabilities of GaN power devices. LiDAR has been confined to scientific and space applications but it is now expanding into mass market for automotive, both in the robo-taxi segment and the ADAS vehicle segment, which requires new technologies and new industries. For EV DC/DC converter application, high-frequency drive is required for miniaturization, GaN is a cornerstone technology for power electronics enabling smaller and lighter electric vehicles, according to Denso International, a leading tier 1 automotive supplier. According to Yole's market research, in this context, the GaN power business could reach around $420 million by 2023, with 93 % CAGR between 2017 and 2023.

For charging EV's workings groups within standards organizations have, around the world, defined everything from the operational envelope and charging sequence, to the communication and connectors of High Power Chargers (HPC). In Europe and the US interested parties have coalesced around CharIN and the Combined Charging System (CCS). Elsewhere other alternatives have developed, such as CHAdeMO in Japan and GB/T in China. Some vehicle manufacturers have also placed value on developing proprietary charging solutions. Here SiC devices, including diodes and switches, will form an essential part of the design choices made, starting at the rectification stages and moving through to the DC/DC topologies chosen to deliver the battery charging output (see our cover story). And on the upcoming PCIM the holy grail of power semiconductors, diamond, will be opened by a paper from a German research institute presenting the in-circuit operation of a **diamond** Schottky diode in a non-isolated buck converter for LED application, a quantum leap in power electronics! Have a look in our PCIM preview.

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

# Renewables Become Key for a Climate-Safe Future

As the urgency to take bold climate action grows, new analysis by the International Renewable Energy Agency (IRENA) finds that scaling-up renewable energy combined with electrification could deliver more than three quarters of the energy-related emission reductions needed to meet global climate goals.

According to the latest edition of IRENA's Global Energy Transformation Report " A Roadmap to 2050", launched at the Berlin Energy Transition Dialogue, pathways to meet 86 % of global power demand with renewable energy exist. Electricity would cover half of the global final energy mix. Global power supply would more than double over this period, with the bulk of it generated from renewable energy, mostly solar PV and wind. "The race to secure a climate safe future has entered a decisive phase," said IRENA Director-General Francesco La Camera. "Renewable energy is the most effective and readily-available solution for reversing the trend of rising CO2 emissions. A combination of renewable energy with a deeper electrification can achieve 75 % of the energy-related emission reduction needed."

An accelerated energy transition in line with the Roadmap 2050 would also save the global economy up to $160 trillion cumulatively over the next 30 years in avoided health costs, energy subsidies and climate damages. Every dollar spent on energy transition would pay off up to seven times. The global economy would grow by 2.5 % in 2050. However, climate damages can lead to significant socioeconomic losses. "The shift towards renewables makes economic sense," added La Camera. "By mid-century, the global economy would be larger, and jobs created in the energy sector would boost global employment by 0.2 %. Policies to promote a just, fair and inclusive transition could maximise the benefits for different countries, regions and communities. This would also accelerate the achievement of affordable and universal energy access. The global energy transformation goes beyond a transformation of the energy sector. It is a transformation of our economies and societies."

But action is lagging, the report warns. While energy-related CO2 emissions continued to grow by over 1 % annually on average in the last five years, emissions would need to decline by 70 % below their current level by 2050 to meet global climate goals. This calls for a significant increase in national ambition and more aggressive renewable energy and climate targets. IRENA's roadmap recommends that national policy should focus on zero-carbon long-term strategies. It also highlights the need to boost and harness systemic innovation. This includes fostering smarter energy systems through digitalization as well as the coupling of end-use sectors, particularly heating and cooling and transport, via greater electrification, promoting decentralization and designing flexible power grids.

**https://irena.org**

**Accelerating energy transformation will meet climate objectives while creating jobs and fostering economic growth** **Source: IRENA**

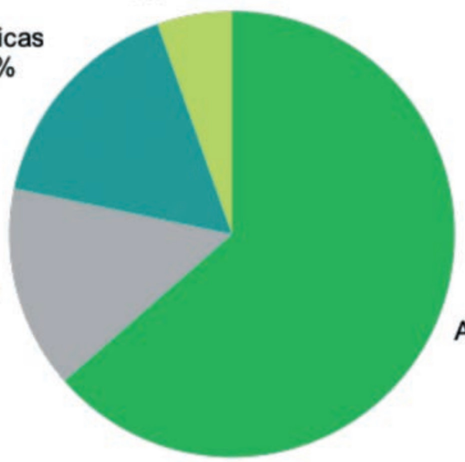
# Global Solar PV Market Returns to Double-Digit Growth

The global solar PV market is set to bounce back from single-digit growth in 2018 to 25 % growth in 2019, reaching 129 GW of solar installations, according to information provider IHS Markit. This revived growth comes mainly from markets outside of China, which are forecast to rise by 43 % in 2019. Spain, Vietnam and other countries have 2019 deadlines for project completions, as falling module prices at the end of 2018 have led to increased demand.

Given the current indications of development activity, China, the world's largest PV market, could grow by 2 % in 2019, after reaching 45 GW in 2018. The majority of these installations would come in the second half of the year, according to the latest "PV Installations Tracker" from IHS Markit. "Right now, the outlook for China remains highly uncertain, as the new support scheme for PV is yet to be announced," said Josefin Berg, research and analysis manager. "Plans to focus policy more on unsubsidized PV systems could slow near-term deployment, unless strict construction deadlines are imposed to spur 2019 demand."

The USA is forecast to overtake India in 2019, to once again become the second-largest PV market. As the 30 % investment tax credit (ITC) ends this year, some projects will rush to meet completion. However, the safe harbor provisions introduced in 2018, which require a 5 % investment to be made by the end of 2019 to enjoy the full ITC rate, have also shifted projected installations from 2019 to later years. "Increasing project development activity shows that the years after 2019 will be booming," Berg said. In India, the push toward lower tender prices, at a time when components have become more costly through safeguard duties, has delayed several tenders and could shake up the future Indian solar PV market. Europe is the region with the largest upswing over the past year, after the minimum import price on modules ended. Installations grew by 23 % in 2018, reaching 12 GW and is forecast to surpass 19 GW in 2019. The revived utility-scale market in Spain alone makes installations almost 60 % of growth in the region.

As solar becomes increasingly competitive with conventional sources of power generation, companies are investing in the renewables industry, as never before, attracted by the growing revenue opportunities and the pressure to increase sustainability. Solar and other renewables are also playing a key role in the decentralization and digitalization of the power system, or the so-called 'energy transition', which is now on the agendas of many governments,




**PV installation forecast 2019** **Source: IHS Markit 2019**

companies and other institutions. "IHS Predictions for the PV industry in 2019," identifies the following significant trends that will drive the market this year:

- Revamping and repowering of PV plants will grow in importance, as the installed base in Europe ages. At the start of 2019, more than 40 GW of PV systems in Europe larger than 100 kW were more than six years old. Technology costs have fallen dramatically since these installations were completed, so upgrading older PV plants to improve their yield and return on investment is becoming more commonplace.
- China's policy decisions will continue to define global dynamics, as it drives its domestic market toward grid-parity projects. With China accounting for an estimated 65 % of PV module production in 2018 and 41 % of global installations, the country clearly dictates the supply-and-demand balance of the industry. This trend will be more pronounced than ever in 2019, as the industry awaits confirmation of anticipated changes to the country's incentive policies.
- More than 500 MWh of batteries will be deployed in utility-scale solar plants in North America. The combination of intermittent renewables and batteries has long been considered the key to providing scalable, dispatchable, clean power. In 2019, the first meaningful volumes of these systems will be installed.
- Diversification of PV inverter suppliers will continue, as they continue to battle stagnating revenues. PV inverter suppliers will continue to expand into a diverse range of adjacent industries as price pressure and intense competition persists.
- The race for the 400-W PV module will heat up as high efficiency products gain share in the market. Solar PV has become a highly competitive energy source, as the average price of a solar panel has fallen by over 80 percent in the last decade. However, these cost improvements have been aided by ongoing improvements in cell and module efficiencies, which have increased by approximately 25 % during the same period.
- There will be 11 million new connections to the Internet of Energy from solar systems in 2019. Digitalization of the grid continues to be a megatrend for the power sector and in the solar industry. IHS Markit forecasts an average of 30,000 new PV inverters will be shipped each day in 2019 or 11 million for the full year.

**www.ihsmarkit.com**

# Acceleration in SiC MOSFETs Patent Filing

The 2016-2018 period has been crucial for the whole SiC industry. SiC MOSFETs, commercially available for several years, are gaining the confidence of numerous customers and have clearly begun to penetrate into different applications. The IP landscape confirms the trend with the strong leadership of the Japanese companies, the entrance of the Chinese players, as well as an impressive penetration rate within the automotive industry.

Yole Développement's sister company Knowmade predicts a $1.5 billion market in 2023, with a 31 % CAGR between 2017 and 2023. As a consequence, numerous players are wondering if the supply chain is ready to embrace such market acceleration. "Attracted by the market potential, there are plenty of players who want to enter the market together with heated competition from power device giants", comments Hong Lin, Senior Technology & Market Analyst at Yole. "The competition has intensified".

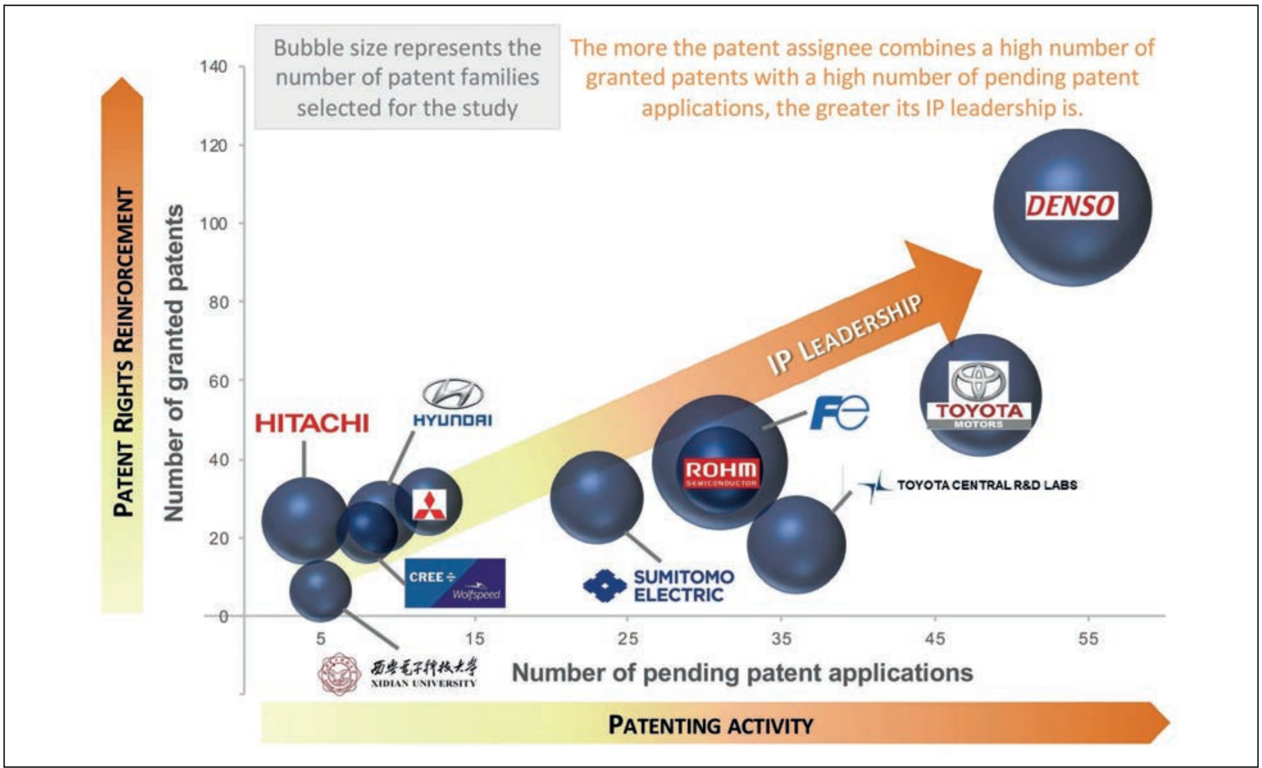
What exactly is the status of the IP ecosystem? Who are the current leaders? Who will have the best IP in the coming years? Knowmade's analyses attempt to provide an up-to-date overview of the SiC IP ecosystem. Knowmade identified a remarkable acceleration in patent filing related to SiC MOSFETs between 2011 and 2015, concomitant with the commercialization of the first

SiC MOSFET products. Japanese integrators, especially Denso and Fuji Electric, have taken the lead in SiC MOSFET related patenting activity. In parallel, China has entered the SiC MOSFET patent landscape in recent years, starting with R&D players in 2011. These were followed by major state-owned integrator companies in 2015, such as State Grid Corporation of China (SGCC), CRRC and SiC pure player IDM Century Goldray, which was established in 2010 to address the whole power SiC supply chain. "The common feature of these new entrants is that they intend to develop IP on both planar and trench MOSFET structures", explained Knowmade analyst Rémi Comyn. In addition, Taiwan has a long-standing R&D player in SiC MOSFETs with ITRI, but there was no industrial player until 2016 when Hestia Power emerged, focusing on cost effective planar JBS diode-integrated MOSFET structures. "We note that current leading SiC device makers like Cree/Wolfspeed, Rohm, Infineon Technologies and STMicroelectonics own some key patents but do not necessarily have strong IP leadership," added Rémi. IP analysis from Knowmade includes dedicated sections focused on planar/trench SiC MOSFETs, SiC Schottky Barrier Diodes as well as SiC power modules.

As a consequence of this growth, the industrial SiC supply chain is constantly evolving. For power devices, the foundry and IDM model are both developing. Between 2017 and 2018, Yole's analysts highlight the following trends: The foundry model is clearly developing. This industry evolution is facilitating the SiC fab-less and fab-lite companies in launching SiC products and making the technology more accessible to the industry.

Under this dynamic ecosystem, Knowmade has released a dedicated patent landscape analysis, Power SiC: MOSFETs, SBDs and Modules. This report provides a detailed picture of the industrial & research IP ecosystem for SiC-based power electronic products, from MOSFETs to Schottky barrier diodes including power modules. Covering worldwide patents published up to October 2018, it offers a comprehensive analysis of more than 1,600 patent families.

**www.yole.fr**




**CTrensch SiC MOSFET IP leadership opf patent assignees**

| | Planar SiC MOSFET | Trench SiC MOSFET | SiC SBD | SiC Power Module |
|---|---|---|---|---|
| Key IP players with steady or increasing patenting active | General Electric | Denso Corporation<br>Fuji Electric | Mitsubishi Electric | Hitachi |
| Key IP players with lower patenting activity since 2015 | CREE/Wolfspeed<br>Fuji Electric | CREE/Wolfspeed | CREE/Wolfspeed<br>Panasonic | Mitsubishi Electric |
| IP Challengers | | Toyota Motor<br>Toyota CRDL<br>Rohm | Fuji Electric<br>Sumitomo Electric | Rohm<br>CREE/Wolfspeed |
| IP new entrants | Hestia Power<br>Century Goldray<br>CRRC Times Electric<br>SGCC<br>UESTC | Century Goldray<br>UESTC<br>SGCC | Shenzhen BASiC Semiconductor<br>Beijing Yandong Microelectronic<br>Century Goldray Semiconductor<br>SGCC | Danfoss Silicon Power<br>Tyco Tianrun Semiconductor,<br>Yangzhou Guoyang Electronic<br>Wancheng Electric Vehicle<br>Operation |

IP collaboration
R&D collaboration

**Key IP players for SiC MOSFETs, SBDs and power modules**

**Source (2): Yole/ Knowmade 2019**

# Silicon/GaN Integration Targeting On-Chip 48 V Input Power Conversion

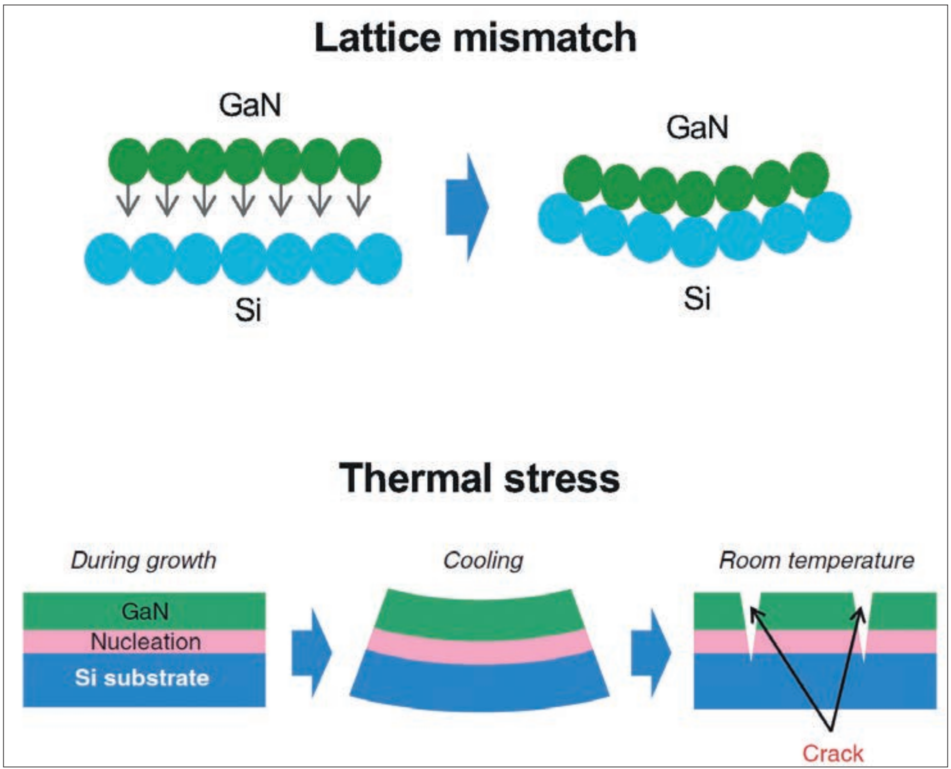
A method for co-integrating GaN and Si has been described by IBM at APEC 2019 that may permit fabrication in a conventional CMOS process flow using large area substrates. The patterned GaN cascodes demonstrate comparable electrical characteristics compared to those of conventional blanket GaN HEMTs grown on Si, as well as a reduction in wafer bow and current collapse.

Silicon CMOS is not compatible with high-voltage or high-power-density applications, such as those for photovoltaic inverters, electric vehicle charging, and DC power transmission. Because GaN is better suited for these applications, co-integration of GaN with Si may provide a pathway for both high power and high performance applications on a single chip. Various co-integration schemes have already been explored including direct bonding and heteroepitaxy. However, high stress during blanket GaN growth on Si limits the wafer diameter due to excessive bowing.

The MOCVD technique (Metal Organic Chemical Vapor Phase Deposition) enables very thin layers of atoms to be deposited on a semiconductor wafer and is a key process for manufacturing III-V compound semiconductors, especially GaN-based semiconductors. The deposition process occurs within a reactor chamber, allowing deposition of the semiconductor layers onto the substrate surface at different temperatures of up to roughly 1,200°C. The MOCVD process allows uniform deposition of ultrathin film layers of below 1-nm-thickness on substrates

Through the growth of MOCVD, Si substrate with the GaN layer has a concave shape due to different coeffients of expansion between Si and GaN layers. If the curvature of the substrate exceeds the mechanical limit of the wafer, the GaN layer will crack over the entire wafer. Thus a so-called buffer layer between Si and GaN is introduced to limit the mechanical stress, but leads to unwanted elctrical effects.

GaN-on-Si co-integration using patterned structures permits the use of 200 mm or larger diameter substrates. The electrical characteristics of co-integrated GaN HEMTs are equivalent to those obtained from GaN on blanket Silicon substrate.

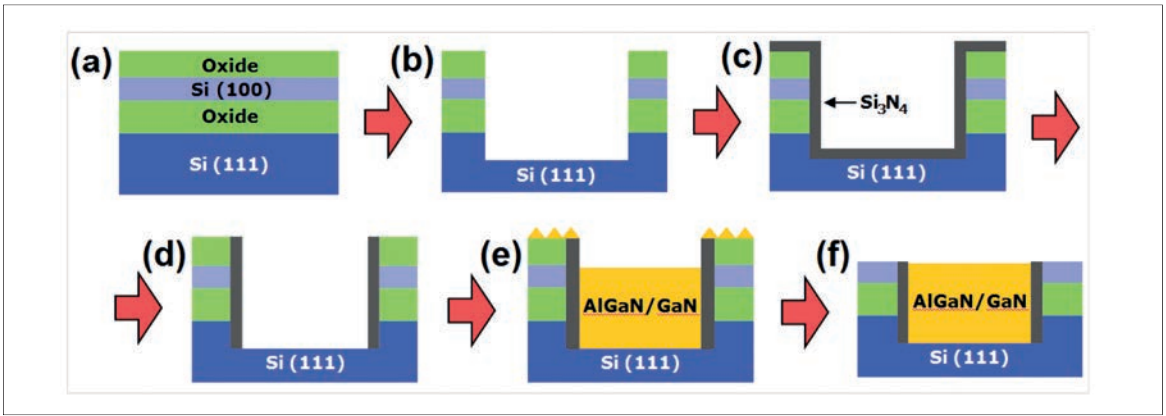



ABOVE: GaN growth on Si limits the wafer diameter due to excessive bowing – leading to lattice mismatch and cracks

### Fully Integrated GaN-on-Si Devices

This approach eliminate cracks and dislocation by growing GaN in the selective area. Fully-integrated GaN/Si-cascode connection can be achieved with adjustable $V_{TH}$, and undesirable parasitic elements caused by integration can be reduced.

Hybrid oriented SOI substrates with 80 nm Si (100)/145 nm buried oxide/750 µm Si (111) were used in this study to permit epitaxial growth of hexagonal GaN on the exposed (111) surface regions while permitting Si CMOS fabrication on the (100) surface. The thickness of top Si (100)




LEFT: Hybrid-oriented SOI substrate with top Si (100) and bottom Si (111) preparation for MOCVD growth: (a) CVD-SiO 2 growth, (b) dry etching to expose Si (111) plane, (c) $Si_3N_4$ growth via CVD as an isolation and diffusion barrier, (d) $Si_3N_4$ removal via dry etch to expose Si (111) plane, (e) AlGaN/GaN HEMT growth, (f) CVD-SiO2 removal via chemical-mechanical planarization

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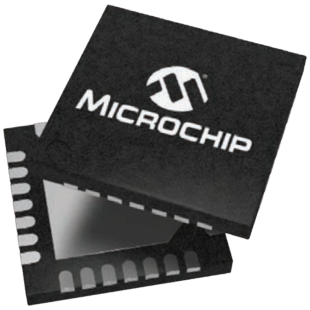


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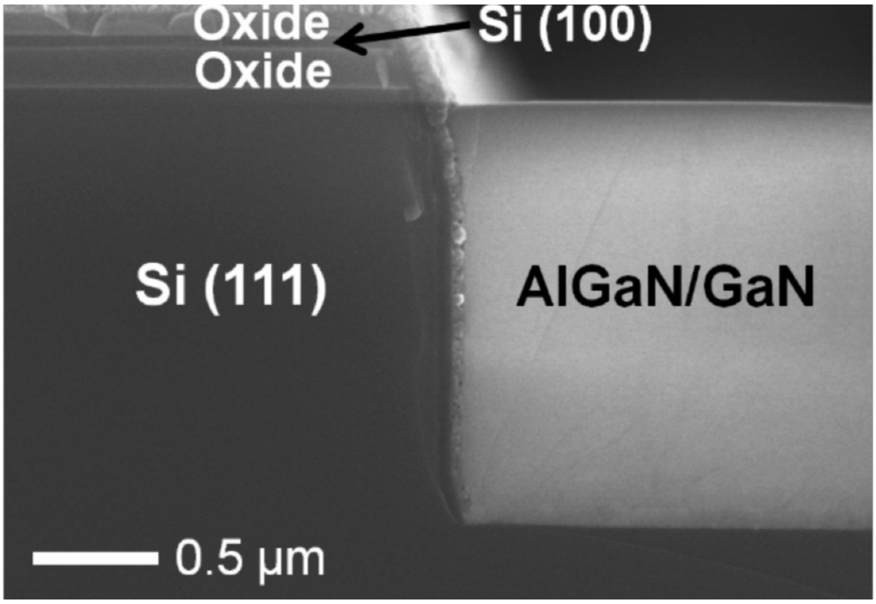



**SEM cross-section of AlGaN/GaN epitaxial growth of 1.5 ?m in the window**

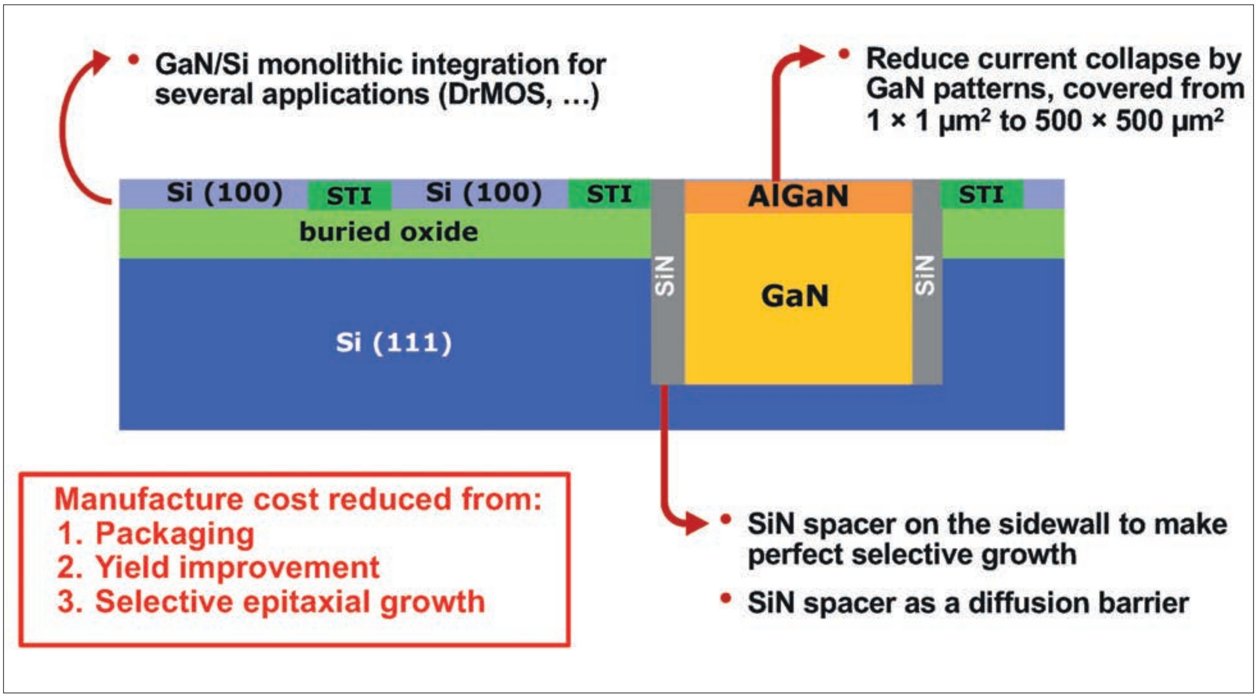
layer was adjusted to 40 nm by thermal oxidation to meet the requirement of the 14 nm CMOS technology node.

Patterned regions of various dimensions, ranging from 50 × 50 μm² to 200 × 200 μm² were created in the SOI substrate by reactive ion etching (RIE) to expose Si (111) below the buried oxide layer to permit selective GaN growth. The percentage of surface area covered by GaN was nominally 35 %, 37 %, 39 % and 41 % for 50 × 50 μm² , 100 × 100 μm² , 150 × 150 μm² and 200 × 200 μm² windows, respectively. The total GaN coverage was limited to less than 50 % to maintain the bow and warp within the Si CMOS specification. $Si_3N_4$ spacers on the sidewalls of the patterned regions were formed to allow electrical isolation between neighboring Si and GaN devices.

Additionally, these spacers provide growth selectivity, and a barrier to inter diffusion of Si and GaN into neighboring GaN and Si regions, respectively, during the GaN growth. GaN growth was performed on both patterned hybrid SOI and blanket Si (111) substrates in a commercial MOCVD reactor operated with high purity trimethylaluminum (TMAl), trimethylgallium (TMGa) and ammonia (NH3) precursors. Growth parameters were optimized to reduce wafer bow below 50 ?m required for Si CMOS processing. The substrate underwent a pre-bake in $H_2$ at 1050°C for 1.5 minutes prior to the growth of an AlN nucleation layer (130 nm) and 1.5 μm of GaN growth at 1035°C. Post growth ramp down occurred at 985°C to facilitate unintentional carbon doping in GaN. The HEMT structure subsequently grown on the GaN contained a 1 nm AlN spacer, 20 nm $Al_{0.25}$ $Ga_{0.75}N$, and a 3 nm GaN cap layer.

**Summary**

GaN devices are promising for the 48 V/380 V architecture, which provides efficiency and compactness for the next-gen HPC systems. Fully integrated GaN-on-Si technology has better performance, eliminate cracks, made GaN/Si




Key technologies of IBM GaN-on-Si

cascode connection compact, and reduce undesirable parasitics. Despite the fact that the mobilities are lower than those obtained from the HEMTs grown on blanket Si (111), the patterned growth can relive the strain without forming cracks in the epitaxial films, which is crucial to wafer-level integration. Fabrication in a conventional 200 mm CMOS fab has already been performed, but more engineering effort should be made to productize it.

**Literature**


"Fully Integrated GaN-on-Si Technology Targeting On-Chip 48V Input Power Conversion", Applied Power Electronic Conference - March 21, 2019

"GaN Devices on a 200 mm Si Platform Targeting Heterogeneous Integration", IBM T. J. Watson Research Center


www.research.ibm.com/labs/watson/

# Powering New Applications

The Applied Power Electronics Conference (APEC) 2019 from March 17 – 21 in Anaheim/California was setting a land mark for the power electronics community in early 2019. The event attracted more than 6,600 delegates compared to the 5,500 in 2018. This success story is largely due to the fact that power electronics are getting more importance in our daily life not only in powering our electric or electronic devices, but also industrial automation (Industry 4.0), transportation (EV/HEV/traction) or IT (cloud computing/datacenters). For all these applications active power devices such as transistors (Si/SiC/GaN), power moules and passive components (capacitors/inductors) play a vital role. All these subjects as well as market trends have been covered in numeropus APEC sessions and presentations.

First in the Plenary Session Vicor's CEO, Patrizio Vinciarelli (**www.vicorpower.com**) received the 2019 IEEE William E. Newell Power Electronics Award for his visionary leadership in the development of high-efficiency, high-power-density power conversion components for distributed power system applications. According to the IEEE Awards Bord "Smaller and more efficient power modules have accelerated the evolution of distributed power architectures, enabling power systems with higher efficiency, power density, and other key performance attributes. Patrizio Vinciarelli's patented contributions led to new power distribution architectures, Zero-Current Switching (ZCS) and Zero-Voltage Switching (ZVS) power conversion topologies, and advanced power packaging. His Factorized Power Architecture (FPA) leveraged current multiplication modules that can efficiently deliver hundreds of amperes at voltages less than 1V. His Converter Housed in Package (CHiP) scalable packaging technology has enabled higher levels of power system efficiency and density. Patrizio Vinciarelli is the named inventor of 151 U.S. patents".

**Vicor's CEO, Patrizio Vinciarelli received the 2019 IEEE William E. Newell Power Electronics Award at the APEC Plenary Session** **Photo: AS**

### Boom for power semiconductors

The boom in the power electronics semiconductor market is mainly due to the increase in sales of IGBT devices for EV/HEVs and motor drives. EV/HEVs will account for almost $1.8 billion worth of MOSFETs and more than $1.9 billion in the IGBT market, including both discretes and modules. MOSFET demand will also be driven by EV/HEV and by networking and telecommunications, which is booming with an 8.3 % compound annual growth rate (CAGR) between 2017 and 2023 due to the installation of 5G network infrastructure. Globally, Yole (**www.yole.fr**) expects a very positive perspective over the next five years, with a 4 % CAGR between 2017 and 2023 for the power device market. "It is worth remembering that no system can live without power, and with the increase in innovation and new technology there is the need to keep the evolution of the power semiconductor industry on track as this is the starting point," said Yole analyst Ana Villamor in the Industry Session "Market Research".

To understand this industry, it is important to recognize that power electronics is application driven, not technology driven. In recent years this market has grown thanks to megatrends such as the arrival of the digital era or environmental issues. "We can directly link the latter to governmental funds given by different countries for energy efficiency improvement, increasing sales of new power electronics systems", said Milan Rosina, analyst, Power Electronics & Batteries at Yole.

"As an example, the EV/HEV segment is driven technologically by emission reduction targets, higher efficiency requirements or less dependency on the oil industry. The electrification of passenger vehicles is revolutionizing the power electronics industry from market and business perspectives, as well as from technology innovations."

### Enabler Silicon Carbide

"Power electronics are directly involved in both power generation and propulsion of vehicles", stated Abas Goodarzi, CEO of US Hybrid Corporation (**https://ushybrid.com/**) in his plenary talk. "Power electronics utilizing SiC devices are integrated with the fuel cell engine to provide the highest power density and more than triple the overall efficiency (fuel in, electric power out) with zero tail pipe emission enabling global Green House Gases reduction and Carbon-free economy. Power Electronics become the workhorse enabling future mobility by also enabling the balance of plant system for the fuel cell engines including air compressor, thermal management and fuel processing units".

Thus new semiconductor-based materials at device level - the so-called WBG such as SiC or GaN, are intrinsically advantageous compared to Silicon



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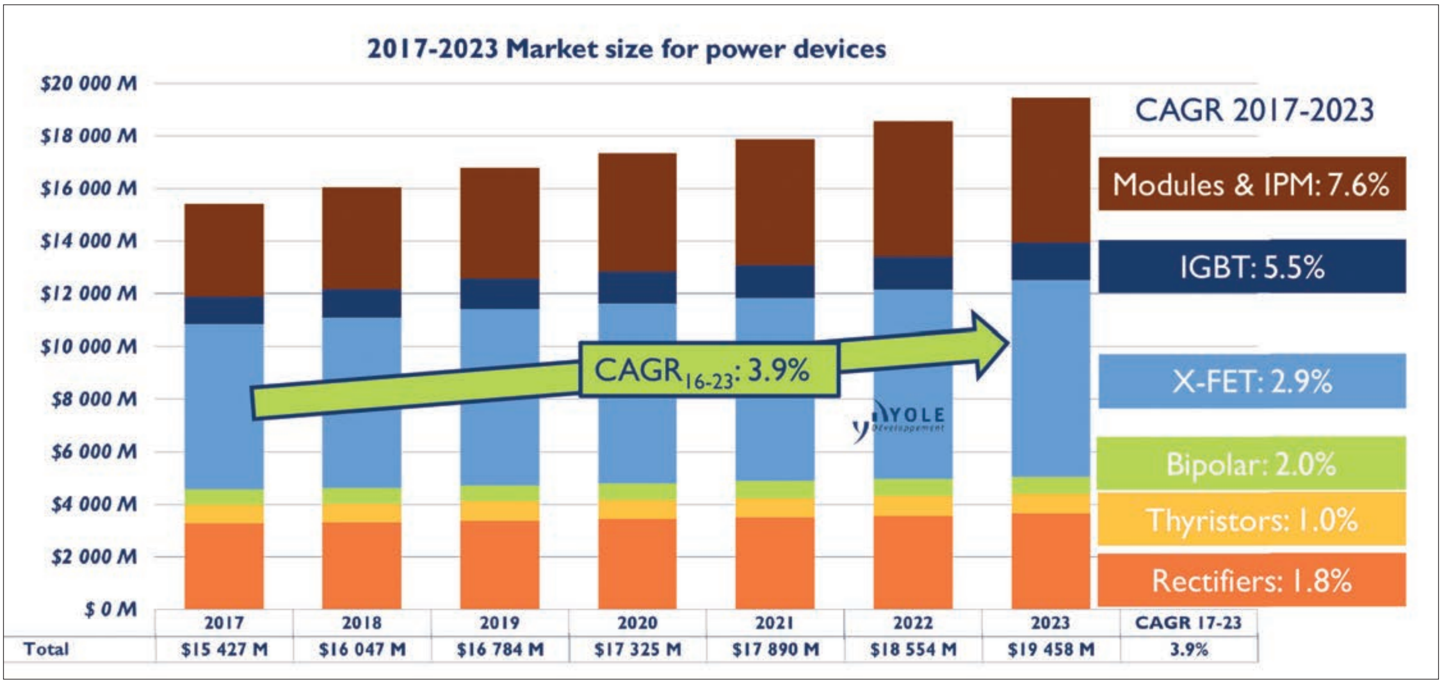



**Power device market 2017 – 2022 by device type** **Source: Yole**

due to their higher band gaps, lower conduction losses, and higher electron mobility. Both SiC and GaN expect to benefit from the arrival of EV/HEV with an increase in production, and to finally have a significant entry into the power semiconductor industry. WBG manufacturers still have few years before large-scale mass production for automotive kicks in, but they are already very active and most of them are in development with OEMs to test their products. SiC products are mainly used in on-board chargers but also to some extent in the main inverter. As from 2017, Chinese automaker BYD uses SiC MOSFETs in some of their on-board charger products. On the other hand, the main inverter market is just starting by Tesla and Toyota. Other car manufacturers expect to have their first SiC-based module prototypes running as from 2020. Yole expects the SiC market for EV/HEV will reach about $400 million by 2022.

Overall Yole predicts a $1.5 billion market in 2023, with a 31 % CAGR between 2017 and 2023.

**Toward ICs with GaN**

Over a long period, industrial companies followed up at a distance the development of GaN-based solutions mainly managed by R&D institutes and laboratories. Today the context has changed.

Eight years have passed since the first commercialized power GaN device appeared on the market by International Rectifier. Today, Efficient Power Conversion (**www.EPC-co.com**), GaN Systems (**www.gansystems.com**), Transphorm (**www.transphormusa.com**) or Navitas (**www.navitassemi.com**) are the innovators in this market, in addition to


**APEC 2019 featured more than 300 exhibitors covering the power components industry** **Photo: AS**

"Today GaN adoption is occurring at 48 V input DC/DC power supplies used in everything, and GaN ICs are coming soon", stated Alex Lidow, EPC's CEO Photo: AS

the power electronics leaders such as Infineon Technologies (**www.infineon.com**) or ON Semiconductor (**www.onsemi.com**). Moreover, not surprisingly, the list of GaN start-up players is getting longer over the years - with Exagan (**www.exagan.com**), GaNWise (**www.ganwise.com**), GaNPower International (**https://iganpower.com/**) or Tagore Technology (**www.tagoretech.com**).

At APEC Alpha and Omega Semiconductor (**www.aosmd.com**) joined the pack by introducing the AONV070V65G1 E-mode GaN 650 V transistor, the initial product in the new aGAN™ technology platform. The device is manufactured on a fully qualified GaN-on-Si substrate technology that has > 50% smaller die area, 10X lower gate charge and eliminates the undesirable body diode reverse recovery charge of Silicon MOSFETs. The ease of use provided by the aGaN technology is enabled by the low on-state gate leakage that allows to drive the transistor with a selection of commercially available Si MOSFET gate drivers. "Our new aGaN technology product platform will enable AOS to provide customers with the next generation of power semiconductor performance enabling system power density and efficiencies not possible with existing Silicon technologies," said David Sheridan, Director of WBG product line at AOS.

Most of the power GaN start-up players choose the foundry model, mostly using TSMC, Episil, or X-Fab as their preferred partner. Meanwhile, other foundries might offer this service if the market takes off. The foundry model affords fabless or fab-lite start-ups the possibility of ramping up quickly if the market suddenly takes off, while existing IDM can benefit from previous acquired equipment and knowledge for GaN manufacturing. "Along with these start-up players, companies with very different profiles are competing in the same playground: industrial giants like Infineon Technologies, ON Semiconductor, STMicroelectronics, Panasonic, and Texas Instruments," commented Yole analyst Ana Villamor.

Even though the current GaN power market remains tiny compared to $32.8 billion Silicon power market, GaN devices are penetrating confidently into different applications. The biggest segment in the power GaN market is still power supply application, for data centers or fast charging for cellphones. "GaN-based power supplies provide the next leap in efficiency and power density due to 50 % higher power density and 20 % lower power losses", explained Shawn Gao of server manufacturer Supermicro


**LEFT: "Our new aGaN technology product platform will enable AOS to provide customers with the next generation of power semiconductor performance not possible with Silicon technologies," said David Sheridan, Director of WBG products Photo: AS**

(**www.supermicro.com**), a GaN Systems customer.

Recently, Exagan and Navitas introduced 45W fast-charging power adaptors with an integrated GaN solution (GaN Fast).

Then, LiDAR (Light Detection and Ranging) applications are high-end solutions that take full benefit of high-frequency switching in GaN power devices. LiDAR has been confined to scientific and space applications but it is now expanding into mass market with the LiDAR market for automotive, both in the robo-taxi segment and the ADAS vehicle segment, which requires new technologies and new industries. LiDAR systems can also benefit from GaN's higher performance.

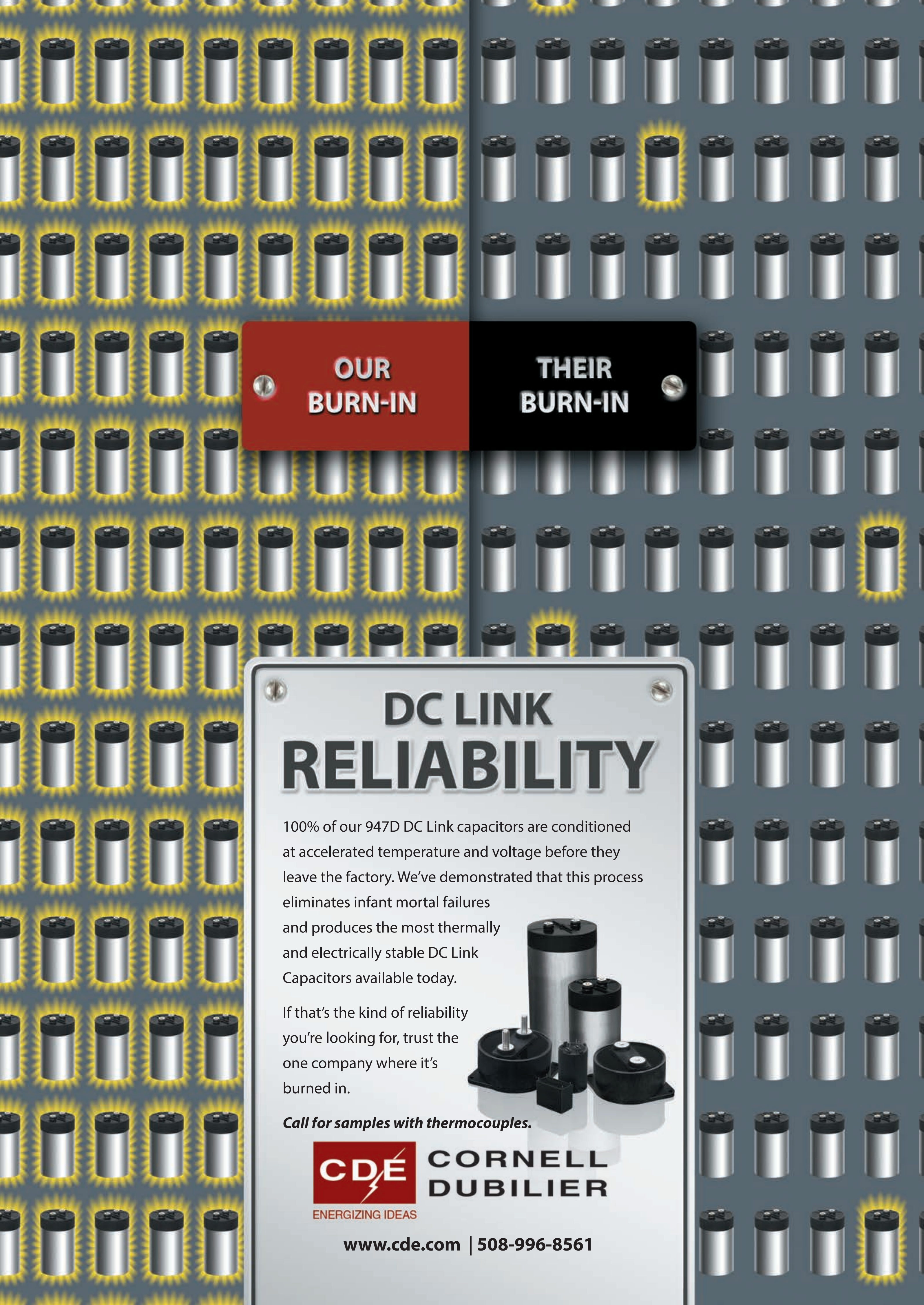
Infineon Technologies announced recently it would start volume production for E-mode CoolGaN 400 V and 600 V based on Panasonic's Gate Injection Technology (GIT). The GaN adoption by the biggest player gives confidence for future market growth.

In parallel, STMicroelectronics (**www.st.com**) and CEA Leti announced their cooperation in developing GaN-on-Si technologies for both diode and transistor on Leti's 200 mm R&D line. Both partners expect to have validated engineering samples in 2019. Also, ST will create a fully qualified manufacturing line, including GaN-on-Si hetero-epitaxy, for initial production running in the company's front-end wafer fab in Tours/France, by 2020. As a good promise, new commercial products arrived during the last year, and more will come in 2019. The main ones released were power supply products for high end or high volume consumer applications. At the moment, each of the segments is targeted by different company profile: integrated solutions for consumer applications and discrete solutions for high-power/high-end power supplies.

"What could be the added-value of GaN technology?", asked Ana Villamor in this Industry Session 5 and gave an answer: Various players, such as EPC and Transphorm, have already obtained automotive qualification in preparation for GaN's potential ramp-up. In addition BMW i Ventures's investment in GaN Systems clearly demonstrates the automotive industry's interest in GaN solutions for EV/HEV technology.

At APEC GaN Systems announced the first 650 V/150 A GaN transistor. "GaN power transistors play a central role in the transition to greater energy efficiency by enabling the creation of smaller, lighter, lower cost, and more efficient power systems that are free from the limitations imposed by Silicon-based solutions. GaN technology enables data center operators and vehicle manufacturers to not only drastically improve their own bottom line, but actually play a role in transforming an energy and data-dependent world", added CEO Jim Witham. "For EV DC/DC converter application, high-frequency drive is required for miniaturization", underpinned Shinya Fukuda from Denso International America in the session "WBG Production Use Cases". "GaN is a


**"From smart robots to collaborative robots, and from virtual fences to energy flexibilization, robotics and thus their power supply play a central role in the Industry 4.0 deployment", stated Peter Hop3, President of Infineon's Industrial Power Control Unit Photo: AS**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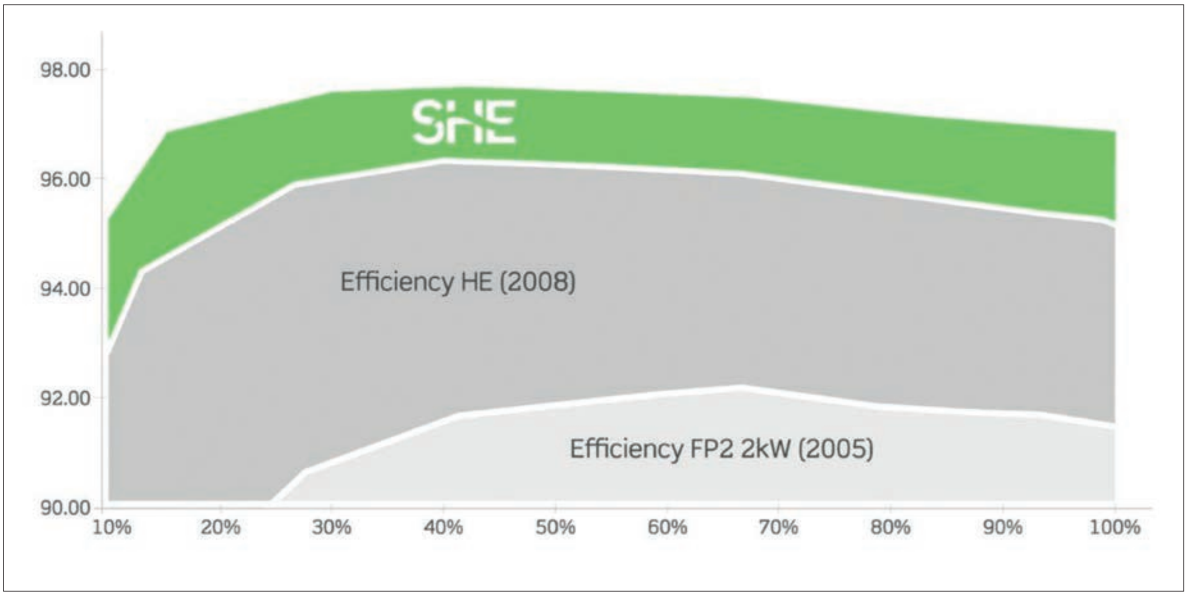



**Efficiency gain of 2 % in an Eltek telecom rectifier resulting by the use of 600 V CoolGaN transistors0**

cornerstone technology for power electronics enabling smaller and lighter electric vehicles".

"With pricing of 100 V GaN transistors equally commercial power MOSFETs, coupled with their large performance advantages, there has been a groundswell of GaN adoption occurring at 48 V input DC/DC power supplies used in everything from AI machines, high-end servers, gaming machines, and now cars", stated Alex Lidow, EPC's CEO at APEC. "Our EPC2052 measures just 1.50 mm x 1.50 mm. Despite the small footprint, operating in a 48 V / 12 V buck converter, the EPC2052 achieves greater than 97 % efficiency at a 10 A output while switching at 500 kHz and greater than 96 % at a 10 A output while switching at 1 MHz, enabling significant system size reductions. In addition, the low cost of the device brings the performance of GaN FETs at a price comparable to silicon MOSFETs. Applications benefiting from this performance, small size, and low cost include 48 V input converters for computing and telecom systems, Lidar, motor drives, and Class-D audio." The just released EPC2053 (3.8 mΩ, 100 V) eGaN FET. joins the EPC2045 (7 mΩ, 100 V), EPC2052 (13.5 mΩ, 100 V) and EPC2051 (25 mΩ, 100 V) to offer a comprehensive family of 100 V products suitable for a wide-range of power levels and price points to meet the increasing demands of 48 V server, 48 V automotive, and 54 V data center applications. Other applications for the 100 V family include single-stage 48 V to load open rack server architectures, USB-C, precision motor drives, LED lighting, and Lidar.

The emergence of cloud based internet services, artificial intelligence, and cryptocurrency has initiated a strong growth of processing power in data centers around the world. Since the data centers are also facing rising electricity and real estate prices, there is a clear trend towards highly efficient and compact server supplies. These new power supplies do not only lead to a lower power consumption of the server, but also to a lower heat dissipation reducing secondary costs such as the cooling of the servers. Typically, state-of-the-art high efficiency power supplies are comprised of a bridgeless or semi-bridgeless PFC stage such as a totem-pole stage and a resonant DC/DC stage such as an LLC converter. For an output voltage of 12 V typically a center tapped transformer is used, while for 48 V systems a full bridge rectification shows better results.

As an example demonstrated by Infineon's Director of GaN Applications Engineering, Eric Persson, Eltek's (**www.eltek.com**) new Flatpack2 SHE telecom rectifier has taken conversion efficiency one step further, from 96 % into the 98 % range, thereby reducing waste by 50 %. The Flatpack2 SHE rectifier is available in a 3000 kW/48 V and 2000 kW/48V version. "Through the use of GaN, in this case CoolGaN, Flatpack 2 SHE is the coolest rectifier ever. We are confident that the Flatpack2 SHE has the most reliable and cost-effective module design. It is based on the same proven concept of the 2 HE, but with efficiency stepped up through the introduction of new and innovative solutions such as GaN power transistors", stated Eltek's R&D Manager Erik Myhre. "With more than 40,000 CoolGaN devices in the field we have not experienced any field failures", Persson underlined. Devices were qualified to Infineon's comprehensive GaN qualication criteria, more on **www.infineon.com/gan**.

The space business shows a convergence of all factors and signs toward a major disruption. "On top of that, there is a new hype for space exploration with a clear need for higher power and higher efficiencies to drive the electrical propulsion systems. The answer from Airbus Space Electronics (www.airbus.com/) includes the use of new technologies like GaN, the implementation of digital control for smart power management, the use of COTs (Commercial Off the Shelf) EEE components and the digitalization & automation of the development process", underlined in the Plenary Session Fernando Gomez-Carpintero, Head of Power Engineering at Airbus Spacecraft Electronics.

Also Renesas (**www.renesas.com/**) offers a radiation hardened portfolio including GaN power conversion ICs for satellites and other harsh environment applications. GaN provides better conductivity and switching characteristics that enable several system benefits, including a reduction in system power losses.

According to Yole's market research, in this context, the GaN power business could reach around $420 million by 2023, with 93 % CAGR between 2017 and 2023. **AS**

# Increasing Efficiency of Display Power Supplies

At APEC 2019 Power Integrations announced the InnoMux™ chipset for display power supplies. The chipset's single-stage power architecture reduces losses in display applications by increasing overall efficiency in constant-voltage and constant-current LED backlight driver stages by 50 % compared to conventional solutions, achieving up to 91 % efficiency. When paired with InnoSwitch3-MX, InnoMux simplifies the power supply design for monitors and TVs by replacing the AC/DC and DC/DC converters with a single-stage flyback topology. The LED backlight control offers minimum threshold regulation as well as analog and several PWM dimming options. The sequenced PWM dimming option further improves visual performance and stabilizes power demand. Extensive protection features such as individual overload protection for all outputs, string imbalanced / short / open protection, and output over-voltage set for auto-restart are provided.

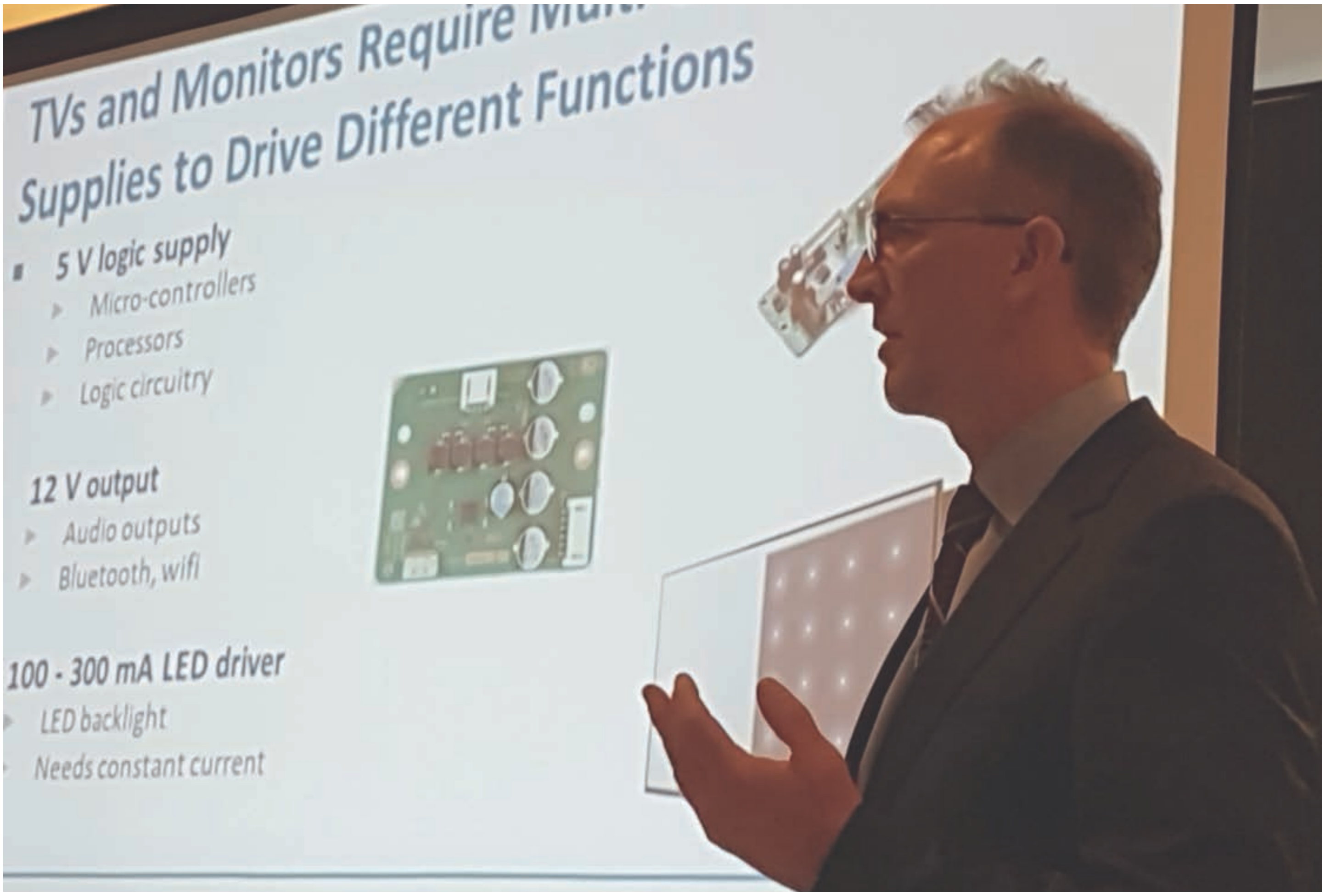
The InnoMux controller (28-lead HSOP package for single-sided wave soldered PCBs or small 28-lead QFN in 5 mm x 5 mm body for compact multilayer designs) consists of a multi-output controller for regulating the three outputs independently, a BP Regulator for supplying both the InnoMux as well as the paired InnoSwitch3-MX secondary controller, high-side MOSFET drivers for directing the energy from the transformer to the appropriate output, shunts to prevent individual outputs from rising in abnormal loading conditions, current sources to drive up to four LED backlight strings, and readers to determine the value of application configuration resistors.

The (paired) InnoSwitch3-MX is the latest flyback switcher IC, combining the primary FET, the primary-side controller, a secondary-side controller for synchronous rectification, and FluxLink™ isolated high-speed communications, which eliminates the need for an optocoupler. The InnoSwitch3-MX receives control information from the InnoMux IC, which independently measures the load requirements of each output and directs the InnoSwitch3-MX switcher to deliver the right amount of power to each of the outputs to maintain accurate regulation of current or voltage; this eliminates the load and cross-regulation challenges seen with conventional multi-output power supplies, making post-regulators unnecessary. Thus overall power conversion efficiency increases by 10 %.

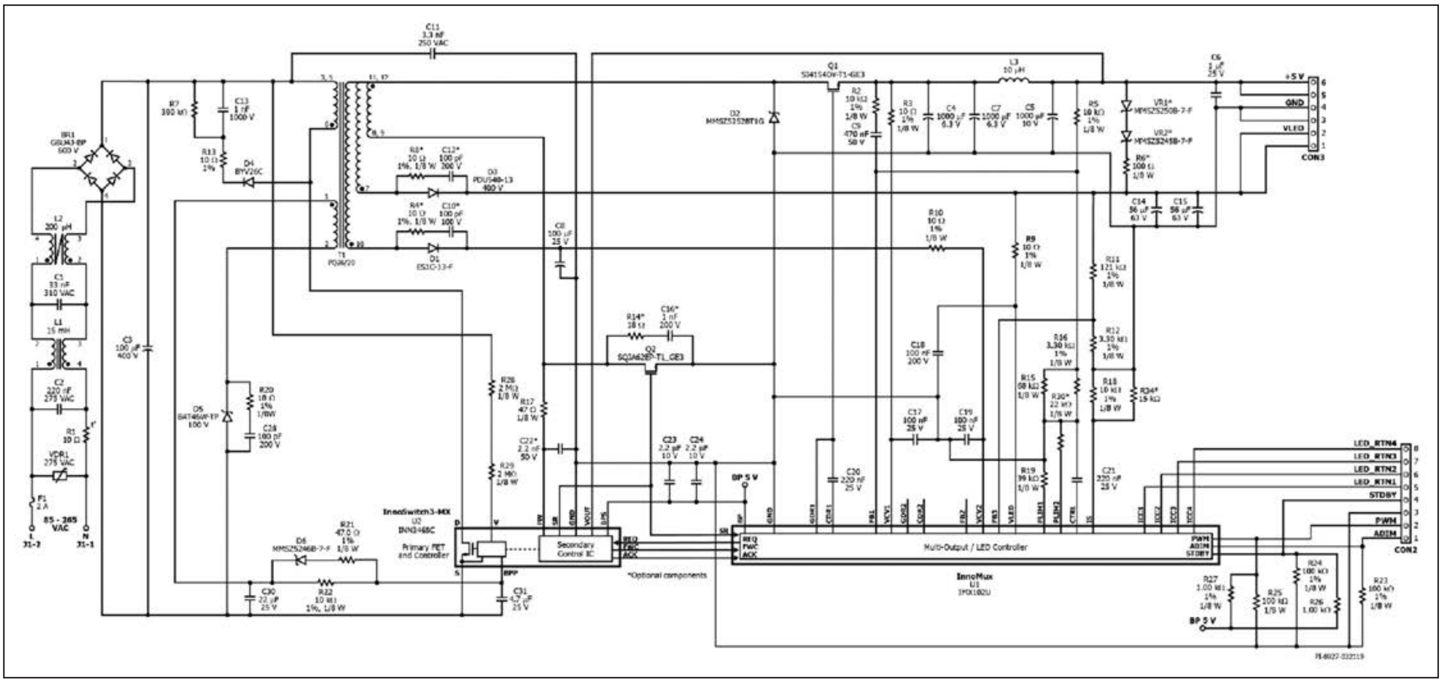
InnoMux supports both accurately regulated constant-current and constant-voltage outputs simultaneously, supplying one to four channels of constant-current and up to two constant-voltage outputs. This flexibility supports the logic, audio and LED requirements typically seen in TV and monitor displays. The IC provides overload protection for each output. InnoMux also supports sophisticated dimming on the LED CC output - analog, PWM, interleaved and hybrid dimming are controlled via dedicated analog and PWM control pins, allowing accurate dimming down to 1.5 %.

**PSU for a LED computer monitor**

The following design example of a 40 W PSU has a 5 V / 3 A CV output and a 25 W output providing power to four CC drivers intended for back-light LED strings in the LED monitor. The input voltage range is 90 VAC to 265 VAC. The




**Douglas Bailey, PI's VP Marketing and Applications introducing the new Innomux IC family** **Photo: AS**

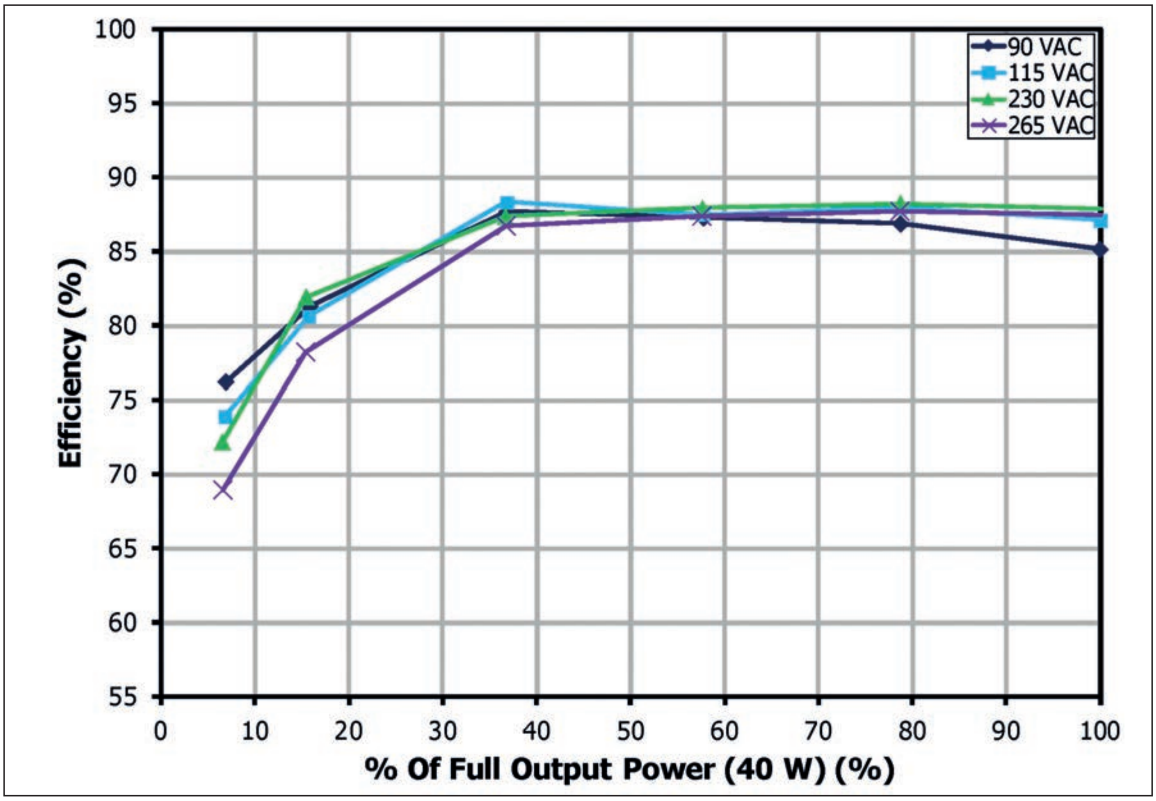


**Schematic of 40 W PSU in multiplexed architecture**

current through the individual LED strings is controlled from 0 mA to 156 mA by an analogue signal (ADIM) with a full scale of 1.5 V.

The PSU is based on a multiplexed, single-stage, multiple output topology shown in the schematic.

For each switching cycle, the energy stored in the transformer during the primary conduction interval is delivered to only one of the converter's main outputs (CV or LED). The energy from the primary is appropriately distributed between the converter main outputs by a secondary referred master controller according to the loading conditions at the outputs. This multiplexing is achieved by gating the steering FET Q1 appropriately. If energy pulse needs to be




**Efficiency vs output power with 30 V LED strings**

delivered to the CV output Q1 it turned ON prior to the end of the primary conduction interval. If Q1 is held OFF the energy is delivered to the LED output via the rectification diode D3. The master controller requests switching cycles from the primary as often as it needs to maintain all outputs in regulation.

For the described multiplexing algorithm to work correctly it is essential that the transformer turns ratios are chosen such that: the minimum LED output voltage reflected to the primary of the transformer is greater than the CV output voltage reflected to the transformer primary. This technique achieves cross regulation within a fraction of 1 % while significantly improving system efficiency when compared to conventional post regulation architectures. The new architecture supports multiple outputs driving both constant current and constant voltage loads, enabling the design of a single switch-mode power conversion stage that powers logic circuitry, USB ports, audio channels, and LED strings simultaneously.

This novel architecture is implemented using two controller ICs, the InnoSwitch3-MX for primary switching plus SR FET control, and InnoMux for output voltage and current control. Selection MOSFET Q1 and D3 are used to direct the energy packet to either the CV or LED output respectively.

**Circuit operation**

A two-stage EMI filter is used on the line AC input, C2/L1 for lower frequencies and C1/L2 for high frequencies. Mainly common mode noise is suppressed by the input filter, but useful suppression of differential noise is also achieved. These measures along with the Y capacitor C11 and screens within the transformer constrain the conducted emissions to below the specification limits. The bulk storage capacitor C3 provides DC voltage smoothing after the bridge rectifier. VDR R1 provides protection against differential voltage surges and the NTC R1 limits the inrush current at power up.

The transformer primary is connected between the rectified DC bus (VIN_DC_TX) and the drain of an integrated power MOSFET within InnoSwitch3-MX (U2 pin 24). Primary current is returned to the bulk capacitor (C3) via the source tab of U2 (pin 16). A low cost RCD clamp, formed by D4, R13, R7 and C13, limits the peak drain voltage due to the effects of transformer leakage inductance and output trace inductance.

The primary side IC is self-starting, using an internal high-voltage current source to charge the BPP pin capacitor C31, when AC is first applied. During normal operation the primary-side of the controller is powered from an auxiliary winding on the transformer. The output of this is configured as a flyback winding which is rectified and filtered using diode D5 and capacitor C30, and fed into the BPP pin via a current limiting resistor R22.

The primary-side output overvoltage protection is obtained using Zener diode D6. In the event of an uncontrolled over-voltage at the output, the increased voltage at the bias winding cause the zener diode D6 to conduct and trigger the OVP protection in the primary-side controller. Resistor R28 and R29 provide line voltage sensing to provide controlled brown in/out behaviour, these are set to approximately 75 VAC and 65 VAC respectively. At approximately 320 VAC, the current through these resistors exceeds the line over-voltage threshold, which results in the disabling of U2.

The secondary-side of the InnoSwitch3-MX (U2) is powered by the BP pin of the InnoMux (U1 pin 15) and decoupled by C2.

The secondary-side of the InnoSwitch3-MX (U2) requests the primary-side to initiate a switching cycle via the FluxLink, a galvanically isolated control channel. This occurs when the InnoMux (U1) raises the REQ pin (U2 pin 1) to the appropriate level.

The gate of the SR FET (Q2) is turned on based on the winding voltage sensed via R5 and the FW pin (U2 pin 9). In continuous conduction mode operation, the SR FET (Q2) is turned off just prior to the secondary-side controller requesting a new switching cycle from the primary side. In discontinuous mode the SR FET (Q2) is turned off when the voltage drop across the Q2 falls below a threshold (V SR(TH) ). Secondary-side control of the primary-side MOSFET ensures that the primary-side power MOSFET and SR FET are never turned on simultaneously. The SR FET gate drive signal is output on the SR pin (U2 pin7) and provides a 5 V drive, so a logic level MOSFET must be used.

The InnoMux secondary-side control IC is powered by +V_LED during start-up via R9 and C18 (optional extra ESD supression) and VLED (U1 pin 23). An internal regulator reduces this to 5 V and outputs it on BP (U1 pin15). Capacitor C24 provides BP5V decoupling for U1. The BP pin output powers the secondary-side controller of the InnoSwitch3-MX.

Once the voltage on VCV2 (U1 pin 21) reaches $VCV2_{MIN}$ (5.8 - 8.0 V) the regulator input is switched from VLED to VCV2 to conserve power. VLED may be up to 100 V whereas VCV2 is usually 6 V – 12 V, the less voltage dropped, the lower the power loss. Resistor R10 and C19 provide optional extra ESD suppression. VCV2 is derived from an unregulated secondary winding in the transformer. The voltage generated by the winding depends on the loading conditions. Critically it provides a minimum of 5.8 V (at light load) supply to the

CV2 pin.

The gate drive to the selection MOSFET Q1 provides a 5 V drive so a logic level MOSFET must be used. Capacitor C20 is charged up to the level of +V_CV1, 5 V in this case, then the –ve end of the capacitor is raised by 5 V, the BP level, to generate the 5 V gate drive pulse. To allow visibility of the idle ring to the FW pin, Q1 is held on after a CV1 or VLED discharge cycle to permit Quasi Resonant switching when in DCM mode. During this time the InnoMux will send a REQ for the next pulse. When an ACK is received Q1 is turned off.

Output rectification for the 5 V output is provided by SR FET (Q2) and CV1 selection MOSFET (Q1). Very low ESR capacitors, C4 and C7, provide filtering, and inductor L3 and capacitor C5 and C6 form a second stage filter that significantly attenuates the high frequency ripple and noise at the 5 V output. Output rectification for the LED output is provided by SR FET (Q2) and diode (D3). Very low ESR capacitors, C14 and C15, provide energy storage and filtering at the LED output.

RC snubber networks comprising R14 and C16 for Q2, R8 and C12 for D3, R4 and C10 for D1 damp high frequency ringing across Diodes/MOSFETs, which results from leakage inductance of the transformer windings and the secondary's trace inductances.

Zener diode D2 is used as a voltage clamp for the transformer CV1 winding while the primary MOSFET is ON and Q1, Q2 are turned off, and D1, D3 are reverse biased. In this condition the secondary windings are floating w.r.t. GND. Without D2, the voltage on Q1 drain could be too high due to transformer winding capacitance interactions.

When the selection MOSFET (Q1) and the SR FET (Q2) are turned on, the transformer secondary windings are designed such that the voltage on the anode of D3 is below the lowest working LED string voltage. Therefore, D3 remains reverse biased and all the transformer energy is directed to the CV1 output via Q1.

When the selection MOSFET (Q1) is turned off and the SR FET (Q2) is turned on, the voltage on the anode of D3 rises until it is forward biased. In this condition all the transformer energy is directed to the LED output.

The LED current per driver is set by R18 and R34 on IS (U1 pin 3) plus, for this application which is configured for Analogue Dimming, the voltage on ADIM (U1 pin 5). The resistance on the IS pin sets the maximum LED current per driver at the maximum ADIM voltage of 1.5 V. Other dimming options are available, such as PWM, Sequenced PWM and combinations of Analogue and PWM. The InnoMux will auto detect the number of LED strings attached.

The STDBY pin is held at BP5V by R26. If STDBY is pulled to GND then the InnoMux enters 'Standby Mode'. Here, the LED driver circuit is powered down, reducing the InnoMux power requirement and the +V_LED output is maintained at a level of at least 15 V. With a standby load of 100 mW on +V_CV1, a Standby power at 230 VAC of under 300 mW can be realized.

**PCB layout**

To minimize crosstalk between the outputs of the converter it is advisable to minimize the length of the connection between the negative terminals of C4 and C7 to the source of SR (Q2). The same applies to the connection from the negative terminals of C14 and C15 to the source of SR (Q2). The two AC paths to the SR source should be kept separate.

Ideally the connection between the GND pins of U1 and U2 should not be shared with any AC ripple current in the output filter stages. This is important for achieving accurate synchronous rectification.

The primary switch in InnoSwitch3-MX is cooled through the SOURCE pin (the paddle) of the IC. Care should be taken that the thermal impedance between the paddle and the cooling copper of the PCB is kept to a minimum. For best results the cooling copper pour should flair out as rapidly as possible away from the solder joint.

The 40 W PSU reaches arounf 87 % efficiency from 35 % load onwards – more or less independently from the input voltage.

Innomux samples will be available in the second quarter via the Power Integrations website at **www.power.com/products/innomux-family.**

# Increasing Potential of Wide Bandgap Semiconductors in Power Electronic Applications

Within ten years of the biannually organized ECPE Wide Bandgap User Forum, many new power electronic systems with wide bandgap (WBG) components and new devices have been reported in research and also commercially on the rapidly moving international market. They use SiC which in the meantime has reached a high level of maturity or, more recently, also GaN (Gallium Nitride) material. Time has thus come to seize on this recent development and to continue the exchange between experts involved in converter and device development.

The 8th ECPE User Forum (March 26 – 27) in Erding/Munich attracted 300+ attendees and thus focused on typical power electronic systems, where the use of WBG semiconductors is highly promising for. Application examples came from the areas of power supplies including inverters for renewable energy and of electric drives also considering increased voltage and power ratings.

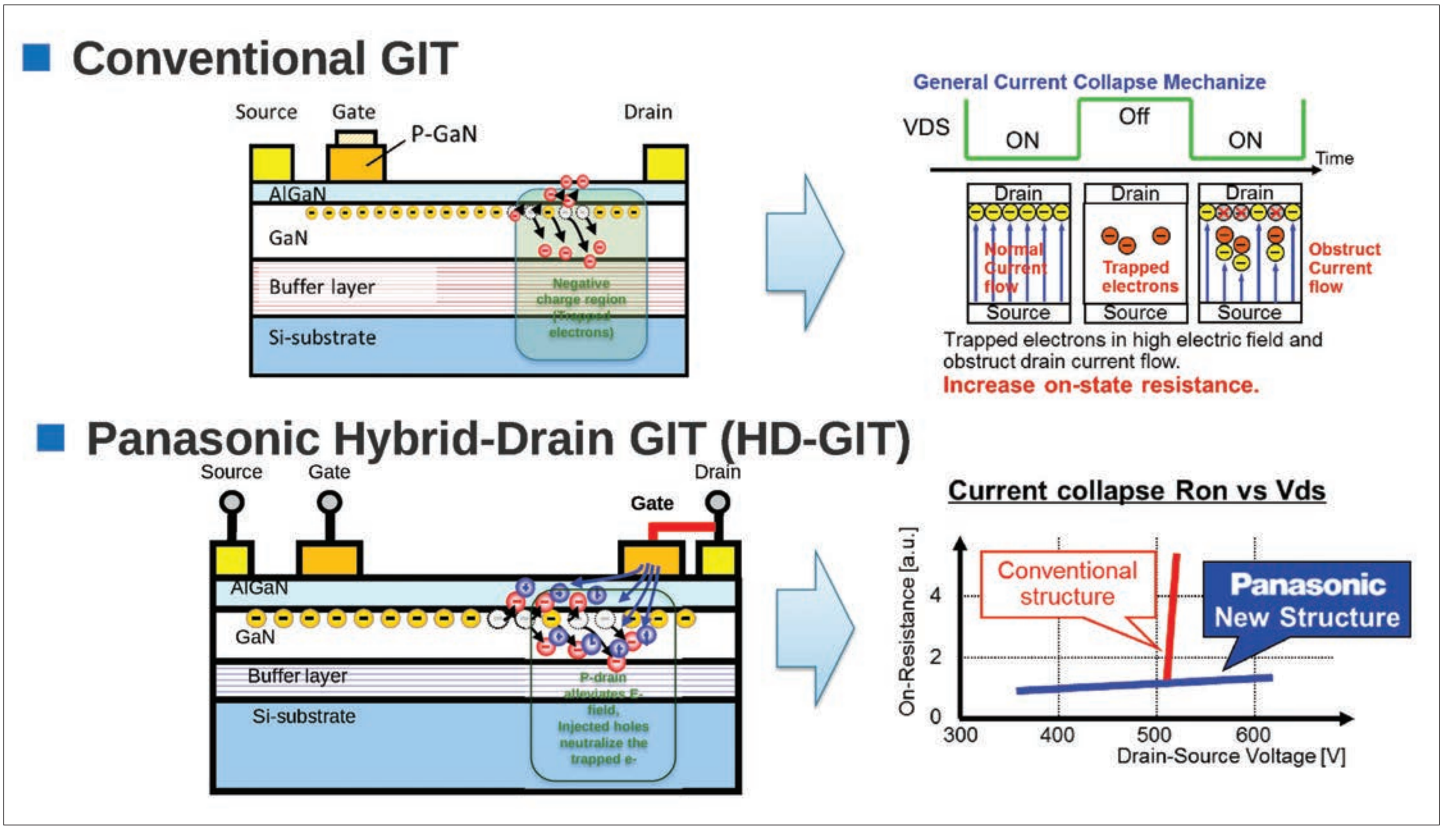
Additionally, insights in recent SiC and GaN material and device technology – which is the base for future system development - has been given for a deeper understanding. International renowned experts gave an overview, to in depth explain their research and development work in technical presentations and to share their knowledge in a discussion forum as an indispensable part of the event.

**State of the Art and Trends**

Several international research programmes and centres have been introduced, contributing to the progress in SiC and GaN devices and systems making use of those. “SiC devices have been found to be beneficial for applications in transportation - in particular automobiles with electric drive, and on a higher power level railway - as they permit to increase efficiency and power density. SiC transistors and diodes may serve in traction converters or power supplies there”, reveals conference chair Andreas Lindemann.

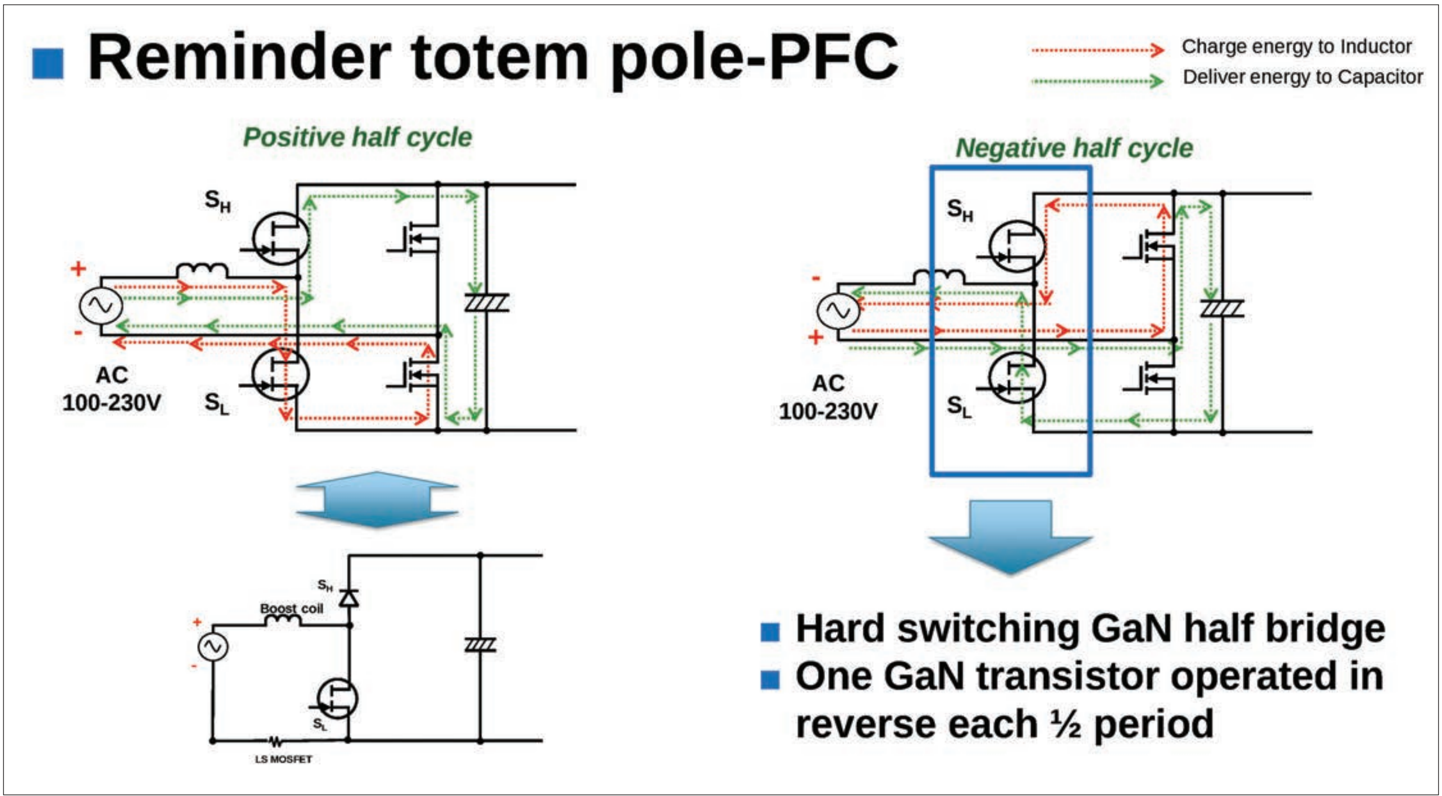
Photovoltaic inverters constitute another important application. Besides, also special applications have been addressed such as high frequency induction heating - remarkably with resonant switching - or converters in the medium voltage grid as currently investigated as a future option. GaN transistors will mainly be rated up to 650 V and used up to voltage levels as supplied by the 230 V single phase grid, e. g. for hard switching power factor correction and similar power supply applications. Obviously the usage of WBG devices requires more than just replacing Silicon devices; instead only an appropriate circuit and system design will allow to fully exploit the potential. This e. g. concerns aspects like the cooling concept, partially permitting to replace fluid by air cooling, or the isolation within the converter and beyond, e. g. in an electrical machine, taking into account the applied voltages and their high change rates. Obviously the passives shall be chosen appropriately as well which in most cases seems possible but will not always rely on standard components. Careful parallel connection of relatively small WBG devices may be required to achieve a high current capability.

With regard to SiC, devices and the related




**GaN transistors are subject to current collapse - a progressive reduction of the conductivity caused by electrons being trapped – and its solution with Panasonic’s HD-GIT**

**Source: Panasonic Europe**




**Estimating the lifetime of a TTP-PFC using GaN under actual operating conditions** **Source: Panasonic Europe**

packaging technology have been addressed where avanced modules and embedding play an increasing role. Drivers dedicated to the transistors are sufficiently fast and make sure good electromagnetic compatibility taking into account the fast switching slopes and the need to maintain controllability. The devices have reached a high degree of maturity, providing good ruggedness e. g. under surge current or avalanche conditions. Their reliability e. g. with respect to gate oxide stability, humidity and load cycles has been qualified; it should however be noted that the applicable test methods partially differ from whath as been established for Silicon devices and that the respective device modelling to understand failure mechanisms still is subject to research.

With respect to GaN research optimization of material and the several types of transistors have been reported. Integration on chip level has been presented as well as hybrid integration and various packaging technologies, ranging from pre-packages e. g. for embedding via chip-scale packages up to more conventional solutions with minimized parasitics. Besides the aspects already mentioned with respect to SiC drivers, GaN drivers need to comply with the different driving conditions or voltages respectively of the devices, maintaining a standard interface towards the control unit.

Major progress has been reported considering parasitic effects like dynamic on-state resistance and current collapse, further also considering breakdown towards the Silicon substrate in integrated lateral GaN devices.

"GaN transistors are subject to current collapse. It's a progressive reduction of the conductivity, caused by electrons being trapped in stable energy levels outside of the conduction band during switching operation", explained Francois Perraud, Head of Power and Automotive Solutions at Panasonic Europe (**www.panasonic.com/de**). The hybrid drain structure introduced by Panasonic solves the current collapse issue from the application point of view: on-resistance stays stable under switching conditions. "It has however been demonstrated that one can extract statistically meaningful acceleration factors related to a specific end of life mechanism of GaN under such switching conditions. Knowing these factors for a given transistor, knowing the maximum current-voltage locus of a given totem pole PFC design, and knowing the application profile in terms of load as a function of the operating time, one can estimate the lifetime of the TTP-PFC using GaN under actual operating conditions", Perraud underlined.

### WBG Applications in Automotive and Aircraft

The first presentation on transportation issues was a good starting point to describe the challenges associated with WBG technologies.

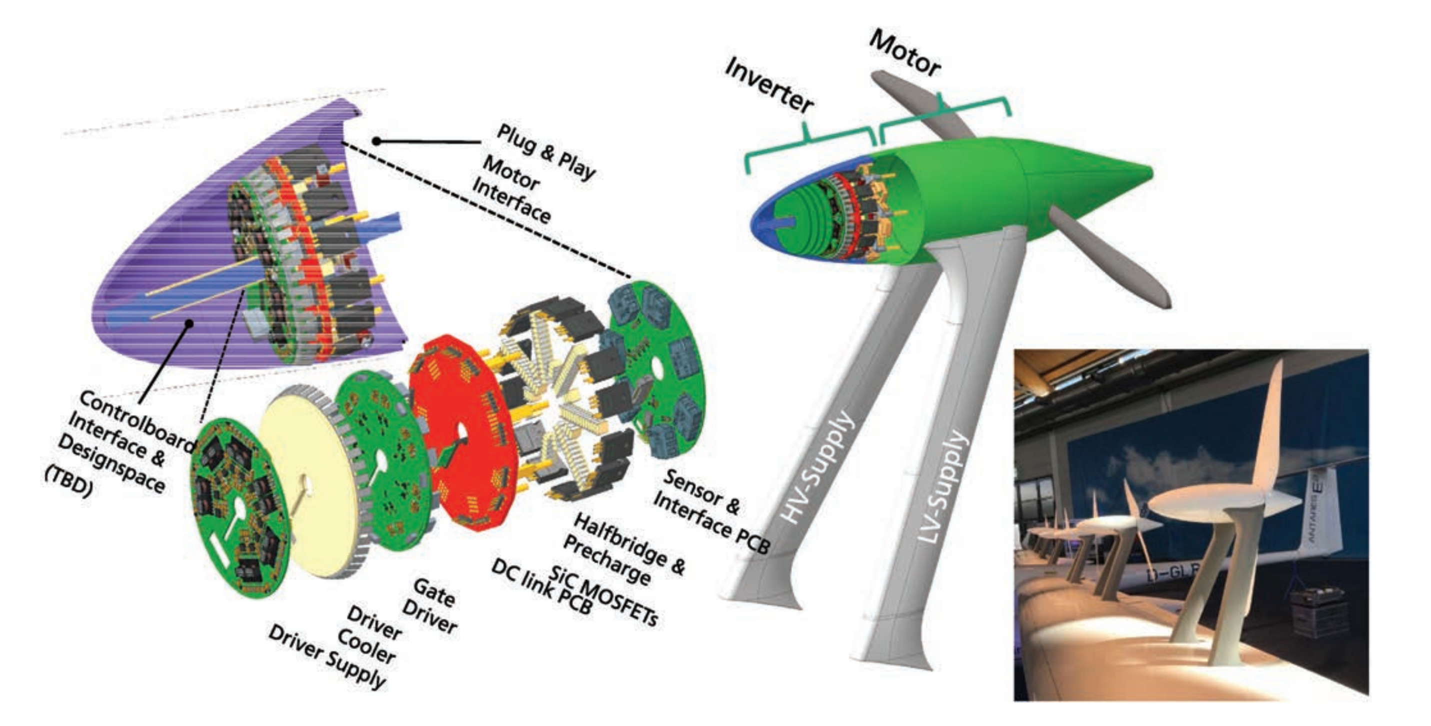
"As an application-oriented research institute, our main interest is to advance into new ranges of system performance and to open up new fields of applications for high performance and cost efficient power electronic solutions. This is both a challenge and an incentive to us. To find creative solutions, we are ready to move off beaten track whenever necessary", so describes Bernd Eckardt, Head of Vehicle Electronic Department of Fraunhofer IISB (**www.iisb.fraunhofer.de**), his job in creating new mobility solutions.

Power electronic systems are key components for any hybrid or electric vehicle. All these vehicles require a high-voltage power net with a voltage above 60 V in addition to the traditional 14 V net. This high-voltage power net must be electrically isolated from the low-voltage net and vehicle chassis for safety reasons.

A high-voltage vehicle power net must contain an electrical energy storage and a traction drive inverter. Highly different vehicle concepts do exist which include further high-voltage power electronic subsystems, such as DC/DC converters for supplying a low-voltage net, inverters for electric air-con compressor, oil or cooling water pumps, DC/DC converters for stabilizing the traction bus voltage, or AC/DC converters for uni- or bi-directional vehicle-to-grid interfaces.

"We permanently strive to open up new applications and functionalities. The grid integration of electric vehicles will gain more and more importance in the future. For avionic applications the new possibilities of modern power electronics will pave the way towards the more electric aircraft. This means powering many more actuators electrically in order to improve the overall fuel economy, and to reduce the maintenance efforts associated with hydraulic systems", Eckhardt underlined.

Novel WBG semiconductors offer the potential for inverter systems with highest efficiencies, power-densities and especially switching frequencies far beyond the stateof-the-art. High-speed electric motors, like compressors and electric turbo-chargers, require higher inverter output-frequencies and therefore higher switching frequencies to avoid additional losses and torque-ripple within the machine. In order to meet these

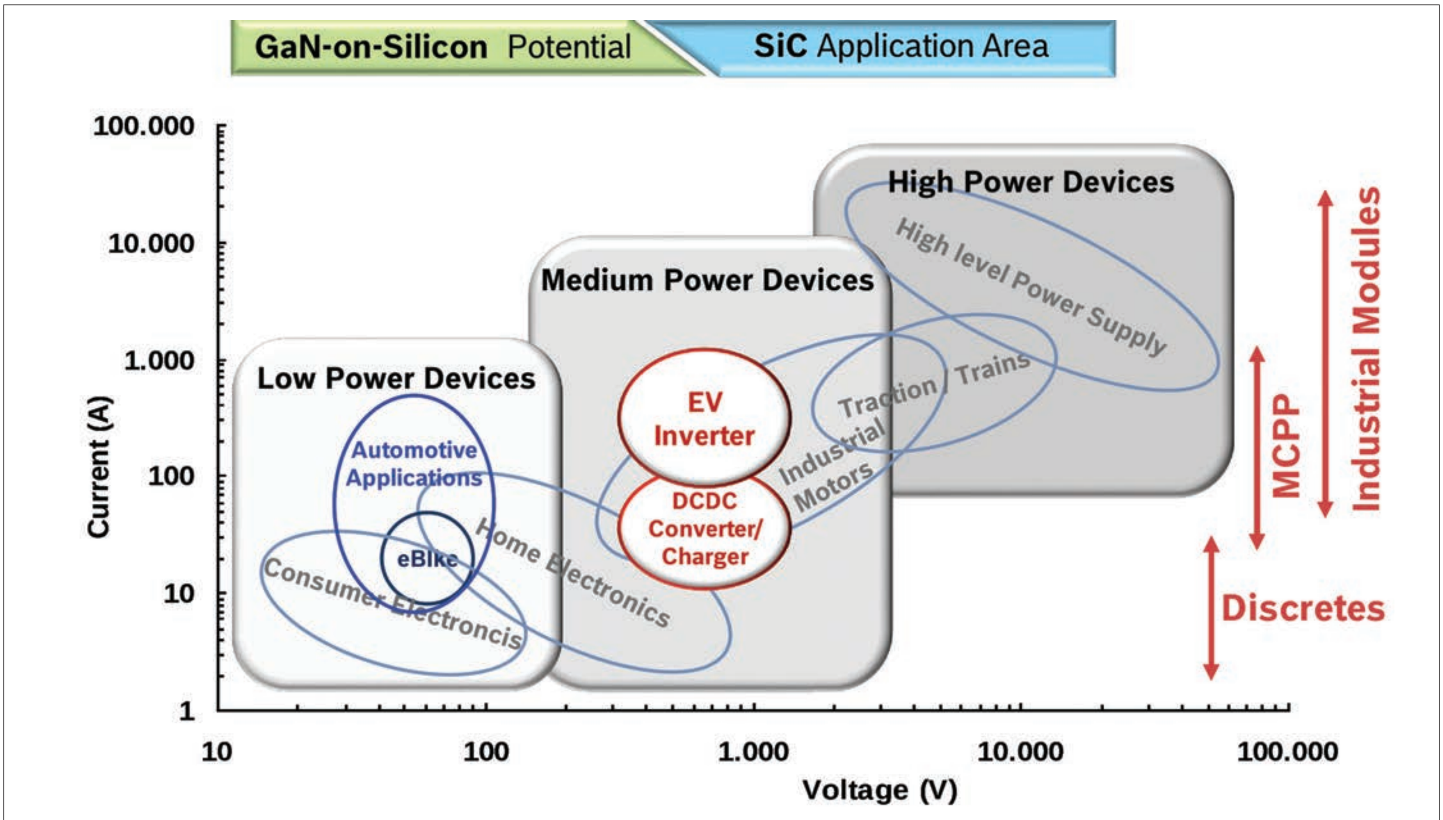



**Concept of mechanical integration - air-cooled inverter with laminar flow body for autonomous aircraft** **Source: Fraunhofer IISB**

demands, investigations and product developments of inverters with WBG semiconductors are carried out. An example is a 60 kW inverter system. The use of 1200 V SiC MOSFETs, ceramic capacitors and a low inductive system design allow switching frequencies up to 100 kHz at reasonable efficiencies. The novel power semiconductors with their reduced losses enable a power-density of the overall power-stage of >150 kW/l which is far beyond state-of-the-art.

The inverter is realized in B6 topology and consists of three half-bridge DCB-power modules equipped with 25 mOhm SiC-MOSFETs. A broad input voltage range from 900 VDC to 200 VDC is covered.

Also an air-cooled inverter with laminar flow body for autonomous aircraft has been designed featuring 14,5 kW continous power at 200 - 300 V battery voltage, a full SiC power stage and with efficiency >98,2 %.




**Potential of WBG technologies in automotive applications** **Source: Robert Bosch GmbH**

The trend towards miniaturization and system integration in power electronics is mainly driven by applications with severe space restrictions such as automotive, robotics or avionic. Major challenges arise from the fact that the installation space in these applications is usually predefined by mechanical requirements with less consideration for power electronics needs. This often results in complex geometries and contamination in addition to high thermal and mechanical stress. However, the better use of space, the avoidance of expensive cables and failure prone connectors, and the reduction of EMI filter expense make it necessary to choose this path. "A mechatronic system integration requires more than just increasing power density. We are working on innovative integration concepts as well as on new device, interconnection, and cooling technologies that foster a 3D integration, increase ruggedness, and decrease costs of power electronics", Eckhardt stated.

"SiC MOSFETs offer the potential to pave the way towards more efficient electric drivetrains", underlined Jens Baringhaus from Robert Bosch GmbH (**www.de.bosch.com**). This way the energy consumption and ecological footprint of future electric vehicles can be significantly lowered. In order to unleash the full performance benefit of SiC based inverters, physical modelling of every component of the system is necessary. Thereby, a realistic benchmark of SiC versus standard

Silicon technology is accomplished. "The optimum choice of semiconductor (Si, SiC, GaN) is not straightforward but requires a full optimization and analysis of all system components and resulting system performance", Baringhaus concluded.

**Conclusion**

"Both, SiC and GaN devices are available and in particular SiC devices are well qualified and widely applied in commercial products. Nevertheless, research, development and also standardization are ongoing to further explore the possibilities of wide bandgap devices in power electronics. The European Center for Power Electronics (ECPE) is a stakeholder in this area, bringing together industrial partners and research institutions", Lindemann concluded.

ECPE will anounce the next SiC & GaN User Forum in conjunction with its annual event in spring 2021, where the progress achieved since today will be reported.

# SEMIKRON Foundation Innovation Award 2019

On ocasion of the SiC & GaN User Forum the Power Electronics Innovation Award was given to two teams - André Haspel and Urs Boehme from Daimler AG in Boeblingen, Germany for their quasi-isolated converter and Johan Le Leslé and Rémy Caillaud from Mitsubishi Electric R&D Centre Europe in Rennes for their work on a high integration, modular 3.3kW AC/DC converter.

André Haspel and Urs Boehme developed an innovative circuit topology for a quasi-isolated converter which allows for two HV systems with different air and creeping distances to be combined and ensures the symmetric distribution of the high voltage potentials in both HV systems. In the event of an insulation error in one subsystem, a safe state is achieved in the other system without excessive stress. The proposed quasi-isolated converter works similarly to a galvanic isolation converter but boasts higher power density with fewer electronic parts. This innovation is designed for use in automotive applications such as high-voltage chargers.

Johan Le Leslé and Rémy Caillaud developed a high integration, modular 3.3kW AC/DC converter for on-board battery chargers. The high efficiency, high power density converter is based on an innovative manufacturing technology where all the components including SiC bare dies, SMT components for the gate drivers and the magnetic core for the inductor are embedded in printed circuit boards. This innovation successfully demonstrates how active and passive components in the kW range can be embedded in PCBs.

The SEMIKRON Young Engineer Award 2019 was given to to Andreas Bendicks from the Technical University of Dortmund for his work on "Active EMI Reduction in Power Electronic Systems by Injecting Synthesized and Synchronized Cancellation Signals" supervised by Prof. Stephan Frei.

Active noise cancellation is a promising approach to suppressing electromagnetic interference (EMI). Existing active EMI filters, however, suffer from unavoidable delay times since they inject a cancellation signal that originates from a measured signal. These delay times limit the suppressible frequency range and the EMI reduction achievable. To resolve this issue, Bendicks' development uses synthesized cancellation signals. Since the signal is artificial, there is no systematic delay and bothersome effects such as phase-shifts or magnitude responses can be compensated for. The only requirement is that the cancellation signal has to be able to be synchronized with the power electronic device to maintain a destructive interference. This can be achieved in most digital controlled systems.

**Innovation awardees Andreas Bendicks (left), André Haspel, Urs Boehme, Emily Heidenreich (SEMIKRON), Bettina Martin (SEMIKRON), Rémy Caillaud, Johan Le Leslé; Prof. Leo Lorenz (ECPE)**

# Full Power at PCIM Europe

Premiering at the PCIM Europe Conference from 7 - 9 May in Nuremberg, research results and developments along the entire value chain of power electronics will be presented. The conference dedicated to practice-oriented developments will highlight the significant trends of wide bandgap (WBG) technologies and high reliable embedded power integrated modules.

With the demand for wide bandgap technologies, participants can look forward to extensive coverage of new GaN device designs including smart driving concepts, improved electrical-, thermal- and reliability-data for SiC components and innovative system designs that manage ultrafast switches in power converters. International experts from industry and academia will demonstrate several solutions on the system level as well as showcase the handling of extremely high di/dt's and dv/dt's inside the package. Talks will include:

- "Highly-Efficient MHz-Class Operation of Boost DC-DC Converters by Using GaN Transistors on GaN with Reduced RonQoss", Shinji Ujita et al, Panasonic, Japan
- "A 3.3kV 1000A High Power Density SiC Power Module with Sintered Copper Die Attach Technology", Kan Yasui, Hitachi Power Semiconductor Device et al, Japan
- "Challenging the 2D-Short Circuit Detection Method for SiC MOSFETs", Patrick Hofstetter et al, University of Bayreuth, Germany

In addition, participants can learn about the benefits of WBG in system designs with advanced passive components. Also at this year's PCIM, new magnetic materials for the next generation of power supplies and filters for motor controls will be discussed in oral and poster presentations.

Discussions will further center on the future development potential for Si based devices, which will remain the key devices for most of high volume system application at least in the next two decades. As Professor Leo Lorenz, General Conference Director of PCIM Europe notes, the event will outline new developments on the next generation Si devices with outstanding electrical performance optimized for particular applications.

Also on the agenda at the PCIM Europe Conference is the hot topic of high reliable embedded power integrated modules achieving outstanding power densities. These relate to the development of new chip contacting technologies with a significant increase in the number of power cycles as well as advanced materials for elevated heat transfer and high isolation property. To achieve this target, the coefficient of thermal extension for all materials used inside the packages including the chip has to be matched. High-level experts will be providing specialist knowledge in the following sessions:

- "GaN Micro-Heater Chip for Power Cycling of


**The Conference Opening by Prof. Leo Lorenz featuring the Award Ceremonies for the Best Paper and Young Engineers is always a highlight of PCIM Europe**

**Source: Mesago_Klaus Mellenthin**


**One aspect to remain in 2019 is the E-mobility forum featuring a lecture program and numerous presentations** **Source: Mesago_Klaus Mellenth**

Die Attach Modules with Ag Sinter Joint and High Temperature Solder", Dongjin Kim, University of Osaka et al, Japan

- "Low Inductive SiC Mold Module with Direct Cooling", Christoph Marczok et al, Fraunhofer Institute IZM, Germany
- "Redundant Liquid Cooled SiC Inverter with Highest Power-to-Weight Ratio for Electrical Drive Applications", Stefan Pfefferlein et al, Siemens, Germany

All contributions are of high relevance to system design engineers. PCIM Europe Conference 2019 will trigger a new research area on high reliable packaging technologies for elevated temperatures with unlimited switching properties for the future development of power converters. As one of the highlights, Conference attendees can learn about the smart embedded power module consisting of ultrafast switches with an innovative integrated cooling system including the bus bar with RF damping on the switching cell directly and DC link capacitor. In addition, four extraordinary Special Sessions will deal with system development trends: "Technologies for DC Grids", "Smart Functions in Power Electronics", "Safety in Motion" and "Smart Transformers".

"This year's PCIM Europe Conference will be offering outstanding presentations covering three main elements of power electronic developments: wide bandgap technologies – devices and system design, highly reliable embedded power packaging technologies with excellent isolation and thermal performance including the management of ultrafast switching devices, and thirdly, future system development aspects for DC power grid including solid state power transformation," summarizes Professor Leo Lorenz, General Conference Director of PCIM Europe.

Highlight on the first day is the opening which includes the The Best Paper Award ceremony honouring the best paper of the conference (sponsored by Power Electronic Europe) as well as the presentation of the Young Engineer Award which goes to the three best lectures from engineers not older than 35 years..

## Keynotes opens conference days

The first keynote will be given at the Tuesday, 7. May 2019, Room Brüssel 1, 9.45 by **Fred Lee**, Virginia Tech, USA, entitled "**Next Generation of Power Supplies**".

In today's power electronics products, quality and reliability are given. Great emphases are placed on high efficiency, high power density and low cost. The current practice has reached a level of maturity that further advances will be closely linked to improvement in power devices, materials, and fabrication techniques. With recent advances in WBG power semiconductor devices, namely, SiC and GaN, we have witnessed significant improvements in efficiency and power density while operating at a frequency an order of magnitude higher than the current practice using Silicon counterparts. With this dramatic increased operating frequency, current design practices are challenged. Design trade off previously considered impractical or inconceivable can be realized not only with significant gain in efficiency and power density, but also drastic improvement of EMI / EMC and manufacturability. Several examples will be given to illustrate the potential impact of WBG devices in performance improvements and ease of manufacturability of future power electronics products.

The second keynote on the Wednesday, 8. May 2019, Room Brüssel 1, 08.45, will be presented by **Ki-Bum Park**, ABB Switzerland, entitled "**The Age of Optimization in Power Electronics**".

Due to the significant growth of renewables, worldwide installation of grid-tied converters is increasing rapidly. To cope with ever-increasing technical challenges in grid connection, recent advances in power electronics optimization in academia is being applied to industrial research as a backbone of developing high power density grid-tied converters. In this talk, in order to push the performance boundaries of the

The PCIM Europe exhibition will exceed 500 companies featuring a complete offering of power electronic devices Source: Mesago_Klaus Mellenthin

current technologies, the impact of each core technology (modulation, topology, magnetics, filter, and Si / SiC) on power densities of the grid-tied converters is explored, which lead to the future research directions with upcoming challenges.

The third keynote on the Thursday, 9. May 2019, Room Brüssel 1, 08.45, will be given by **Jim Witham**, GaN Systems, Canada, entitled "**GaN and Industry 4.0 – A Small Change that is Revolutionizing the Industry**".

As production becomes increasingly automated with a growing dependence on assembly line robotics, sensors and artificial intelligence, new challenges are arising for industrial businesses around capital costs, energy costs and the need for greater flexibility in the layout of the manufacturing floor plan. It is estimated that global industry already accounts for more than 40 % of the world's electricity use, and energy efficiency along with flexibility is becoming increasingly important considerations in the financial bottom line. Power and floor / cabinet space is expensive, but their costs can be reduced, and financial savings generated if motor drive systems are made smaller with increased energy efficiency, power output and function integration. As more of these systems are implemented on the factory floor in a decentralized manner, the ability to use longer and lower cost unshielded cables improves both the bottom line and facility design efficiencies. These automated systems generate and capture increasingly large quantities of data, and data processing (servers and data centers) are increasingly under pressure to achieve greater energy efficiencies.

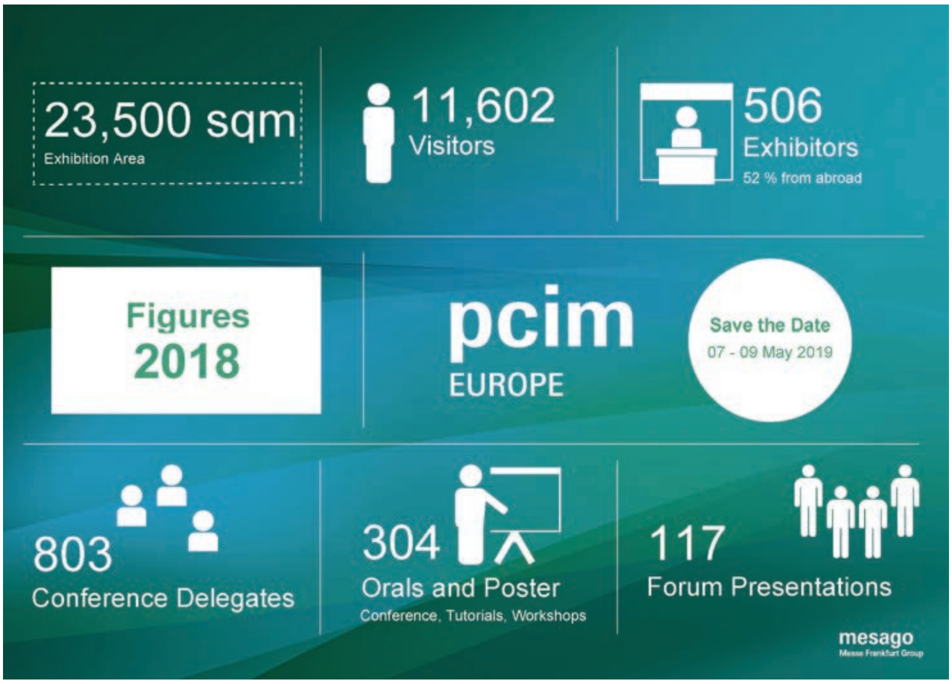
## More conference highlights

- On the Tuesday afternoon the session "Advanced Device Technologies" feature three papers: Bidirectional Switch based on Silicon High Voltage Superjunction MOSFET and TVS Diode Used in Low Voltage DC Solid – State Circuit Breaker; Infineon Technologies
- Short Circuit Detection Methods for SiC Power Semiconductors; University of Kiel, Danfoss Silicon Power, and
- Diamond Schottky Diode in a Non-Isolated Buck Converter; Fraunhofer Institute IAF.

The latter paper presents the in-circuit operation of a **diamond** Schottky diode in a non-isolated buck converter for LED application, a quantum leap in power electronics!

The enormous progress of GaN- and SiC-based power devices proves the advantages of WBG semiconductors in comparison to the established Si-based power devices. The related high critical field strengths of WBG semiconductors leads to devices with low area specific on-state resistances and low switching capacitances. These properties are highly desired for highly efficient and more compact power electronics. However, even higher than GaN and SiC is the bandgap of diamond, resulting in a high critical field strength, furthermore, diamond has a remarkable thermal conductivity. These promising properties are the motivation for ongoing research activities in development of diamond-based power devices. Material quality and device technology is currently improved. Already today diamond Schottky- and PIN-diodes achieve remarkable performance in static- and dynamic- measurement setups. Still outstanding are investigations in power electronic applications. This work presents the in-circuit operation of a diamond Schottky diode in a non-isolated buck converter for LED voltage converter application at mains voltage. The converter with the **diamond Schottky diode** achieves a maximum efficiency of 87 % and a stable in-circuit operation conducting over 200 mA at mains input voltages. This is the first presentation of diamond-based power semiconductors at PCIM!

WBG devices and applications are covered in the sessions "High Voltage SiC" on the Wednesday morning, "GaN System Integration", in the poster session on the afternoon, and in the session "GaN Devices" on the Thursday afternoon.




**2018 PCIM Europe figures – a slighty increase is expected this year**

But Silicon is still the workhorse in power applications, the session "Advanced IGBTs" on the Tuesday morning, "Advanced IGBTs and MOSFETs" or "High-Power Semiconductors" on the Tuesday afternoon are certainly also of interest.

Converters, Inverters, Magnetics or Capacitors are covered in various sessions and complement the theoretical foundations given in the conference. Thus more than 300 oral and poster presentations to more than 800 conference delegates will be given, the organizer expects slightly higher numbers than in 2018.

### Therory meets practise

Once again, this year, the number of exhibiting companies is expected to exceed 500, more than half of them from abroad. All well recognized power electronic companies will exhibit their latest offerings.

At three exhibition forums the PCIM Europe offers a top-quality lecture program – presentations cover topics such as "The Evolution of GaN", "EV/HEV Transformation of the Power Modules Industry" (Yole Développement) and "Thermal Resistance of Interconnect Layers in Inverter Power Stack Assembly" (Alpha Assembly Solutions). In keeping with the motto "Meet the Speaker", those at the Industry forum as well as the E-mobility forum will be available for questions for 15 minutes after their lectures.

For the first time ever, there will be Guided Tours on the trend topic of e-mobility, introducing exhibitors that specialize in this application of power electronics. Interested visitors have the possibility of signing up for these tours online prior to the event. **AS**



# Design Considerations for fast DC Chargers Targeting 350 Kilowatt

Workings groups within standards organisations have, around the world, defined everything from the operational envelope and charging sequence, to the communication and connectors of High Power Chargers (HPC). In Europe and the US interested parties have coalesced around CharIN and the Combined Charging System (CCS). Elsewhere other alternatives have developed, such as CHAdeMO in Japan and GB/T in China. Some vehicle manufacturers have also placed value on developing proprietary charging solutions. For manufacturers looking to address this market it quickly becomes clear that a modular approach is required. The article shows how to proceed in this way. **Pradip Chatterjee, Application Owner of EV Charging, Infineon Technologies, Warstein, Germany**

**The car owner has, unknowingly, been** spoiled for many decades by a seamless network of refuelling stops. The thought of having to plan a journey optimised around the location of gas and service stations is utterly unfamiliar. However, this is probably one of the initial thoughts going through the minds of those considering purchasing or leasing a battery electric vehicle (BEV). Although the automobile is used by many primarily for short journeys well within the range of a BEV, it is the exceptions, such as a weekend away or the annual vacation, that cause concern.

When parked at home our BEV can be charged, slowly, overnight. Many of our larger cities and towns have also started to provide municipal charging piles, enabling us to top-up our vehicle's charge while shopping. The reality is, for longer journeys at least, the charging time has to come somewhere close to that required for refuelling an internal combustion engine vehicle. A 22 kW home AC charger can deliver charge equivalent to around 200 km of range in a time frame of 120 minutes. Reducing this to seven minutes would require a fast DC charger supplying 350 kW.

For manufacturers looking to address this market it quickly becomes clear that a modular approach is required. This allows reuse of some aspects of the end solution, such as a common housing and cooling concept, while connectors, cables and the power electronics can be selected to match the specifications of the target market.

## Approaches to the fast DC charger power electronics design

Fast charging HPC refuelling points will require dedicated electrical low or medium voltage (LV/MV) infrastructure as their supply. It is expected that this will be installed primarily in locations such as motorway service stations along key routes between cities. The incoming AC supply feeds into an isolating transformer whose secondary will be converted to DC. Transformers with a double secondary

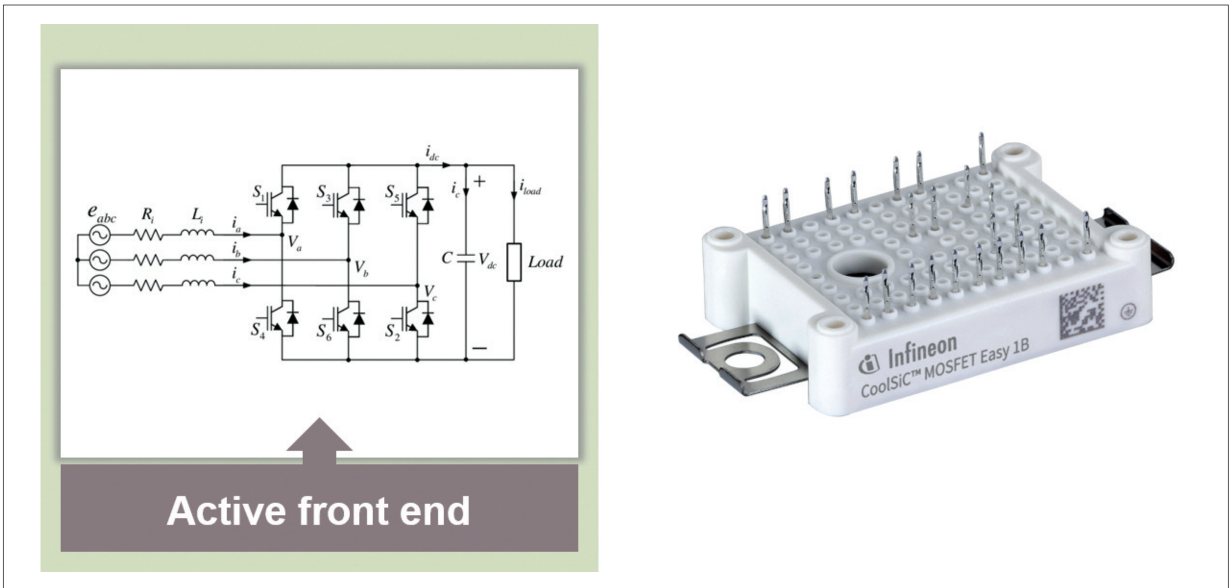



**Figure 1:** An Active Front End can be easily implemented using a single 1200 V CoolSiC™ MOSFET module

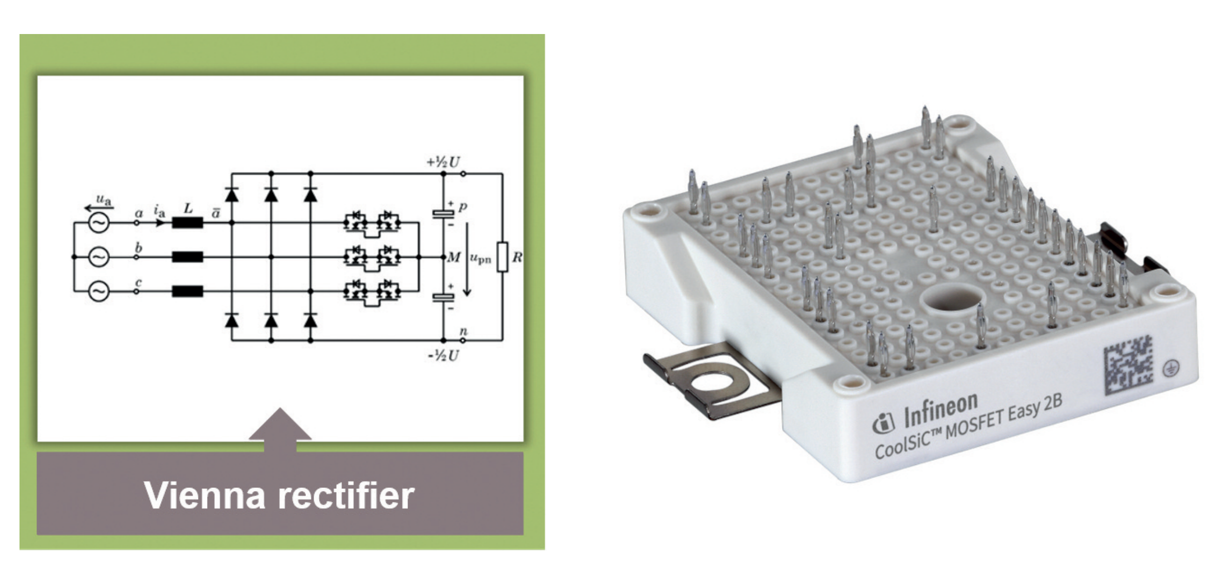



**Figure 2: Half-bridge modules integrated into Easy 2B packages, such as the F3L15MR12W2M1_B69, are ideal for a Vienna rectifier**

Δ and Y winding are a popular solution.

These phase-shifting transformers are then combined with multi-pulse rectifiers operating in series or parallel that reduce harmonic content at the input. In such designs the transformer is mandatory even if isolation can be provided through the chosen topology for the DC/DC stage, mainly due to the harmonic content improvement its presence provides. The first design decision to be made here is whether to take a common AC or common DC bus approach.

In the common AC bus approach, the secondary side of the transformer feeds multiple AC/DC rectifying stages that feed their own DC/DC stages. This has the benefit of simplifying the overall design concept for the charger. However, it does require a replication of the AC/DC stage that results in higher total cost due to the need for several sets of filters, control stages and sensing. Currently, support for injecting energy back into the grid, such as Vehicle-to-Grid (V2G) and Vehicle-to-Building (V2B), is not mandatory. However, should this change, this approach would result in further cost and complexity.

The common DC bus approach uses a single AC/DC stage to create a DC output that supplies all the DC/DC stages. In many cases, this proves more optimal as it reduces device count and cost, and improves overall efficiency. Should V2G and V2B become mandatory it would also be simpler to retrofit. A DC bus is also easier to integrate with other energy systems (local battery storage, photovoltaic) that may be implemented. Finally, current DC charger standards support the idea of a centralized charging station operating as an active front end for several battery chargers. The main downside surrounds dimensioning such a high power-rated active front end.

Charging parks supporting 2 to 3 MW of power prefer the common DC bus, using it to supply between six and eight high-power DC/DC charging stages.

## Focussing on the AC/DC rectification

Thanks to modern power transistor technology, coupled with high performance microcontrollers (MCU) and digital signal processing (DSP), highly efficient AC/DC rectification circuits can be implemented. These ensure a sinusoidal current draw from the grid, low harmonic distortion (THDi ≤ 5 %), and independent control of active and reactive power flow while ensuring high dynamic control. Operation at unit power factor ensures there is no reactive power consumption from the grid. Finally, if the chosen topology supports it, bi-directional power flow between the AC and DC sides is relatively straightforward.

One of the most widely used topologies is the Two-Level Voltage Source Converter (2L-VSC). This consists of an array of six switching devices, typically IGBTs or SiC MOSFETs, together with a capacitor as a DC link, generating an output voltage higher than the input phase voltages. This active front end also supports bi-directional energy flow and provides a fully adjustable power factor. The switching approach can make use of either pulse-width modulation (PWM) or space vector modulation (SVM).

This can be easily implemented using the single-package 1200V CoolSiC™ MOSFET Module FS45MR12W1M1_B11 (Figure 1). This contains six switching devices in the EasyPACK™ 1B package that features a low inductive design and contains an integrated NTC temperature sensor. Half-bridge solutions, such as the FF11MR12W1M1_B11 in the EasyDUAL™ 1B package, could also be considered. Designs based on these components could support 60 to 100 kW at switching frequencies of 25 to 45 kHz.

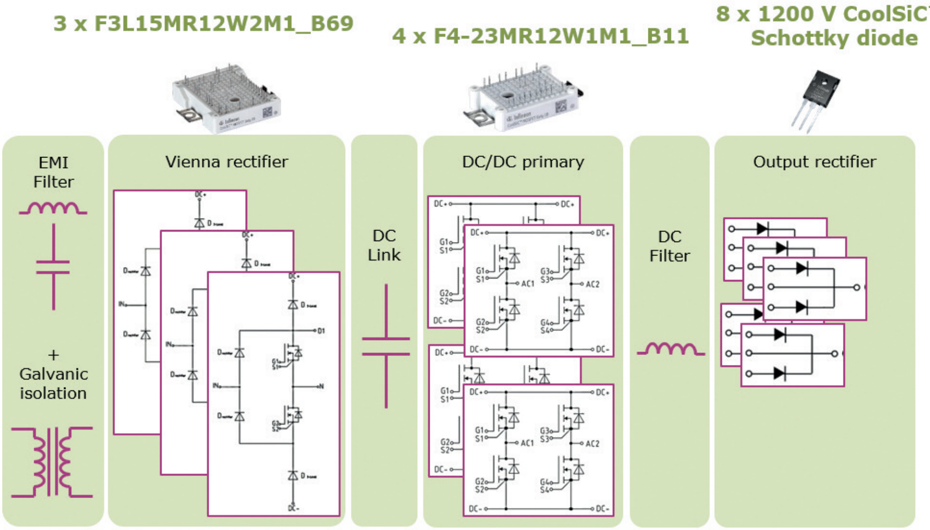
If bi-directional current flow is deemed unnecessary, the three-phase, three-level Vienna rectifier is becoming the popular choice. It requires only three active switches and provides dual boost power factor correction (PFC). In the event of a malfunction in the control circuit it is protected against a short-circuit of the output or front end, and can even operate with the loss of one input phase. Assembly effort for such designs can be high using discrete components, but in such high-power applications, integrated power modules are more commonly used.

A Symmetric Boost PFC Vienna rectifier can be implemented using SiC modules such as the F3L15MR12W2M1_B69, offered in an Easy 2B package (Figure 2). Each module contains two 1200V fast rectifying diodes, two 1600 V slow rectifier diodes, and two 1200 V, 15 mΩ SiC MOSFETs. Three such Easy 2B packages can easily be combined to create a compact high current, low loss design (Figure 3).

## Delivering the variable DC charging voltage

The CharIN specification for DC chargers defines that the supported output voltage must lie between 200 V and 920 V, supply a maximum of 500 A, and operate within a power envelope of 350 kW. There is a range of DC/DC topologies, both isolated and non-isolated, that can be used to tackle this challenge.

Regardless of the topology chosen,




| Stage | Switching Freq. | Devices | Product | Part number | Pcs |
|---|---|---|---|---|---|
| AC/DC | 40 kHz | | 1200 V CoolSiC™ Easy 2B | F3L15MR12W2M1_B69 | 3 |
| | | Driver IC | EiceDRIVER™ 1ED | 1EDI40I12AH | 6 |
| DC/DC | 120 – 140 kHz | | 1200 V CoolSiC™ Easy 1B | F4-23MR12W1M1_B11 | 4 |
| | | | 1200 V CoolSiC diode | IDW40G120C5B | 5 |
| | | Driver IC | EiceDRIVER™ 1EDI | 1EDI60H12AH | 16 |
| µC | | | XMC™ 4000 4x PWM Timers | XMC4400-F100K512 BA | 2 |

**Figure 3: High efficiency 60 kW design utilising Easy 2B Vienna rectifier phase leg modules**

there are several key requirements that need to be fulfilled. Physical size and overall cost are focus areas, while electromagnetic interference (EMI) regulations must also be observed. Zero voltage or zero current switching (ZVS/ZCS), highest efficiency and support for the high power required are also on the list. Finally, low ripple of both voltage and current at the output are essential to avoid battery heating.

Topologies utilizing a high-frequency (HF) isolation transformer, such as a full bridge LLC resonant converter, are known for their high efficiency at their resonant frequency. They are also inherently compact thanks to their ZVS primary side switches and ZCS secondary side diodes. Unfortunately, supporting the desired wide output voltage range makes charger development exceptionally challenging with this approach.

Above 100 kW power outputs, and since the galvanic isolation is guaranteed by the grid transformer, a non-isolated Buck/Boost converter can be used. In a multi-phase configuration, it can provide efficiencies of up to 98.5 percent. This approach also significantly reduces current pulsation due to the shifted voltage pulses. Its modular design allows its dimensions and operational parameters to be easily adapted to changes, both in output and performance or physical shape.



## Managing heat dissipation

Despite the incredible efficiencies that power converters can achieve today, a mere 1 percent drop in efficiency is equivalent to 3.5 kW of power dissipation, emitted as heat, when a fast DC charger is operating at full power. The cable alone can add an additional loss of 100 W per metre length. HPCs require more than a forced air-cooling approach to heat dissipation. Additionally, it is not only the power electronics but also the connector and cable that requires manufactures to move to liquid cooling.

The challenge here is that many liquid coolants have issues with flammability, degradation, corrosion, and toxicity. Today a water-glycol mix has shown itself as a popular coolant for both the cable and connector. Dielectric coolants have also been developed, such as the 3M™ Novec™, with successful deployment in the ITT Cannon HPC. The cooling system is then coupled with a separate or centrally located heat exchanger, depending on the configuration of the charging park.

## Summary

The uptake of BEVs is, to some degree, dependent on the available charging infrastructure. Some worries could be alleviated through better promotion of the existing network of charging points, although investment in fast DC charging HPCs, specifically to diminish range-angst for those worried about their longer journeys, is also required. Liquid cooling will be an essential part of the heat dissipation strategy, requiring that the selected electrical topologies and components are both highly efficient and provide easy integration with the mechanics of the heat extraction approach. SiC devices, including diodes and switches, will form an essential part of the design choices made, starting at the rectification stages and moving through to the DC/DC topologies chosen to deliver the battery charging output.

# Next Generation of Precision Power Analyzer for Drive and EV Technology

As renewable energy, electric vehicles and energy efficient technologies gain wider adoption, the need for reliability in testing efficiency, performance and safety is greatly increasing. With its high accuracy and modular architecture, the new WT5000 empowers engineers to innovate with precision, flexibility and confidence to quickly bring their products from concept to market. **Anoop Gangadharan, Yokogawa Europe, Amersfort, Netherlands**

With a guaranteed accuracy of ±0.03%, harmonic comparisons up to the 500th order and custom computations, the WT5000 delivers multichannel measurements Figure 1). Accuracy specifications are guaranteed from 1 % to 130 % of the selected voltage and current ranges. With minimum influence of low power factor (0.02 % of apparent power) the unit is also accurate at large phase shifts and frequencies.

## Powerful capabilities

Seven slots for user swappable power elements and diverse options can expand or reconfigure the WT5000 as applications and their needs change. Additionally, the speed and torque from 4 separate motors are measurable. WT5000 is fully touchscreen operable, supported by hardware hotkeys and software for remote measurements. The 10.1 inch WXGA touchscreen delivers excellent noise immunity even in high noise environments such as motors and inverters.

The event trigger function allows users to set limits to capture readings that fall within or outside a specific range of power, current or other parameters. Users can also define and use up to 20 different expressions for custom calculations. Data that meets the trigger conditions can be stored, printed, or saved to a USB memory device.

The WT5000 offers up to 32 GB of internal storage memory that can be used to store and recall various custom configurations and test setups. It can also be used to log large amounts of measurement data over long periods of time, behaving just like a logger. This non-volatile memory makes it easy to store data without preparing any external media. Waveform/Numeric/Screen Copy data or Setting Information can be easily saved.

Supported communications include GP-IB, USB and Ethernet, but is also backward compatible with communication commands of previous models.

In addition to low pass frequency filters and line filters, the WT5000 features advanced filtering capabilities that provides control to analyze even tough waveforms with precision.

- Synchronization source filter: Instead of synchronizing to zero crossings, users can select any specific point of the synchronization source signal.
- Enhanced frequency filter: Allows users to simultaneously measure fundamental and switching frequencies without influencing any other parameter.
- Digital Parallel Path filters: Supported by a high frequency anti-aliasing filter, two separate line filters for normal and harmonic measurements ensures accuracy without aliasing in wide band and harmonic measurements. Users can limit the number of harmonic orders to


Figure 1: **Operable by touch and/or hardware hot-keys independently, up to 7 different power phases at 10 MS/s (18 bit) can be measured on the 10.1 inch screen**

**Figure 2: Swapable measurement units at the back with current probes**

eliminate attenuation in low bandwidth measurements.

The WT5000 allows to not only measure harmonics and power simultaneously but also offers side by side comparison of harmonics from two different input sources. The effects of noise and aliasing are minimized by antialiasing and line filters with Digital Parallel Path technology allowing simultaneous power analysis of wide band and narrow band components.

Precision current sensing (Figure 2) is accomplished by coaxial current shunts in the swappable 30 A input element ensuring low resistance, low inductance, low impact on phase shift and minimized heat dissipation. Heat flow pathways are optimized in the shunts and across the instrument to ensure even distribution and minimum effect on resistance.

## Evaluating motors and inverters

Motor drive technology has become more complex in recent years, pure sine-wave PWM is less common, and cases where the mean voltage differs greatly from the fundamental voltage waveform, are more frequent.

Key requirements for drive analysis are:

- Multi-phase measurements from battery, inverter and motor
- Evaluation of motor characteristics such as torque, rotation speed and direction, slip and electrical angle
- Harmonic analysis of inverter signals at various rotational speeds

The WT5000 guarantees a basic power accuracy of ±0.03 %, between 1 % to 130 % of the selected voltage and current measurement ranges, at 50/60 Hz. Simultaneous measurements from the inputs and outputs of boost converter, inverter, and storage battery. In addition to computing power conversion efficiency of inverter and motor (up to 7 power inputs), the WT5000, also allows the measurement of rotational speed, torqueand output (mechanical power) from the analog/pulse inputs of rotation or torque sensor. With the ability to measure harmonics up to the 500th order even at

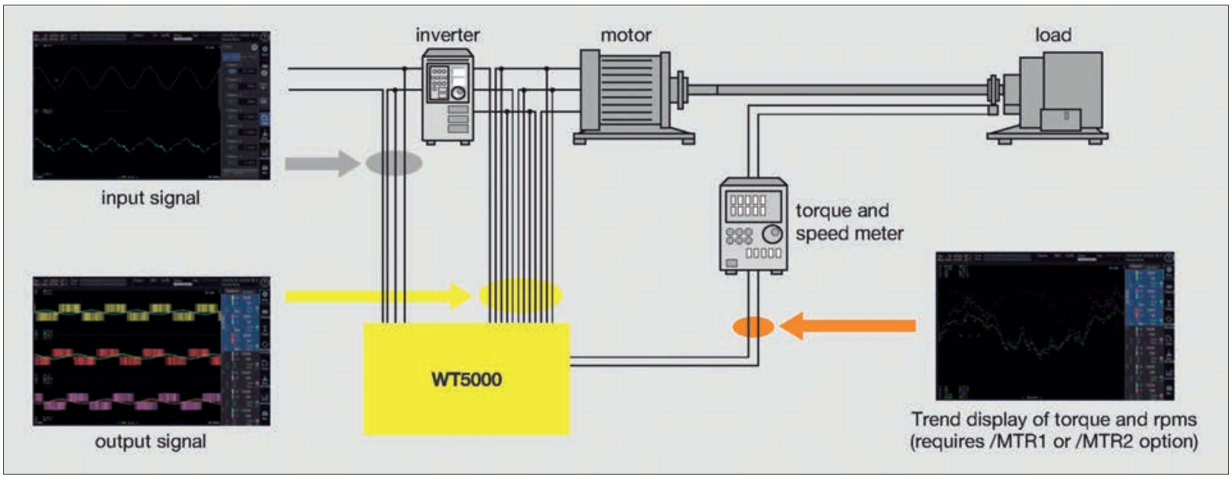



**Figure 3: With multi-channel power measurements, motor evaluation and harmonic comparison capabilities, the WT5000 helps engineers in motor and drive development**

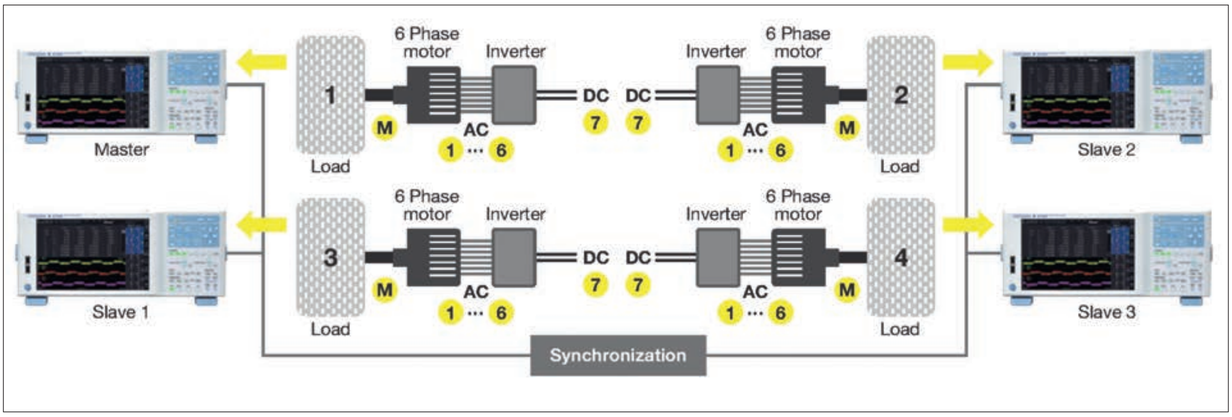



**Figure 4: By synchronizing four WT5000s with one master unit and three slave units, up to 28 input elements for electrical power measurements and up to 16 motor evaluation functions can be accessed**

low rotation speeds the WT5000 supports harmonic analysis without the need of an external sampling clock.

The motor evaluation function enables measurements of rotational speed and direction, synchronous speed, slip, torque, mechanical power, electrical angle and motor efficiency from an analog or pulse output of torque sensors or pulse outputs of rotation sensors. Up to 2 motors can be measured per WT5000 when the determination of the rotation direction and the electrical angle is needed.

However, a simple setting in the motor configuration menu, allows a single WT5000 to take synchronous measurements from up to 4 torque and rotation sensors enabling users to determine the overall efficiency from 4 wheel driven vehicles.

When synchronizing four WT5000s with one master unit and three slave units, users have access to 28 input elements for electrical power measurements and up to 16 motor evaluation functions (Figure 4). The WTViewerE software will support this performance.

## Electric vehicle development

Up to 18 % of the total charge of an electric car is consumed by electric drive system losses. Electric and hybrid car manufacturers therefore need to accurately evaluate motor and inverter control in order to achieve higher precision and greater efficiency. Additionally, the accurate analysis of inverter waveforms without interference from switching noise is a key part of evaluating the motor drive circuit.

Key requirements in this case are:

- Multi-phase measurements from battery, inverter and motor
- Evaluation of motor characteristics such as torque, rotation speed and direction, slip and electrical angle
- Battery charging/discharging characteristics
- Harmonic analysis of inverter signals at various rotation speeds

With high accuracy, multi-channel power measurements, evaluation of up to 4 motors and harmonic comparison capabilities, the WT5000 helps automotive engineers (Figure 5). It enables simultaneous measurements of voltage, current, power, torque, rotation speed, electrical angle and mechanical power. Motor evaluation and mechatronic efficiency can be measured by rotation speed, torque, and output (mechanical power) of motors from analog/pulse inputs of rotation or torque sensors. A single WT5000 can be configured for synchronized measurements from up to 4 motors simultaneously. Battery charging & discharging characteristics can be measured by integration of instantaneous positive and negative values of energy allowing the evaluation of battery charging and discharging characteristics. And with

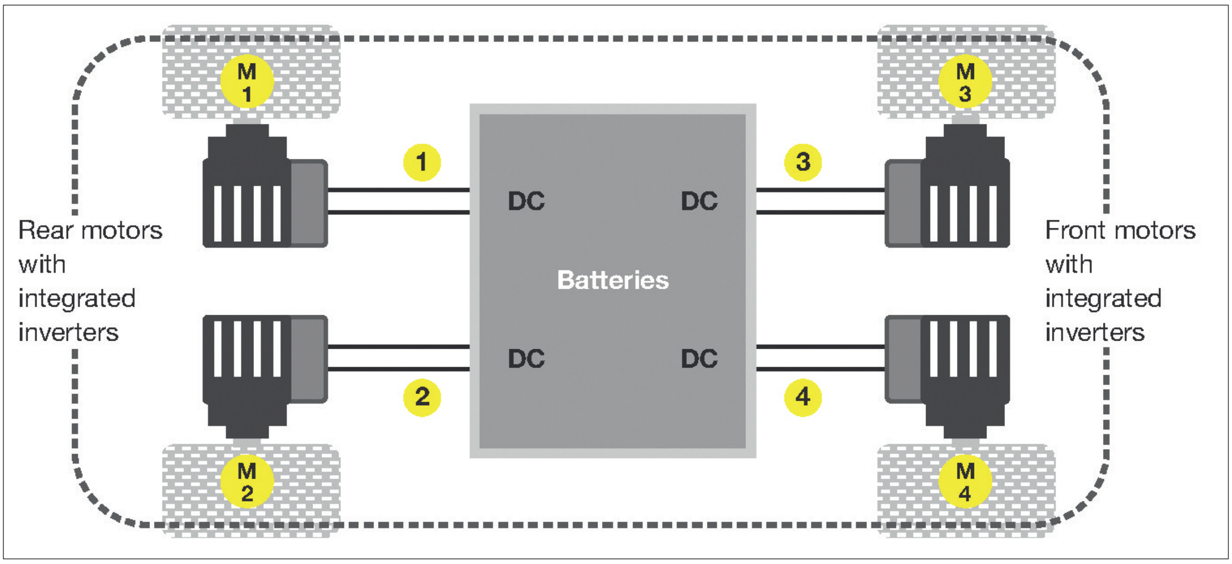
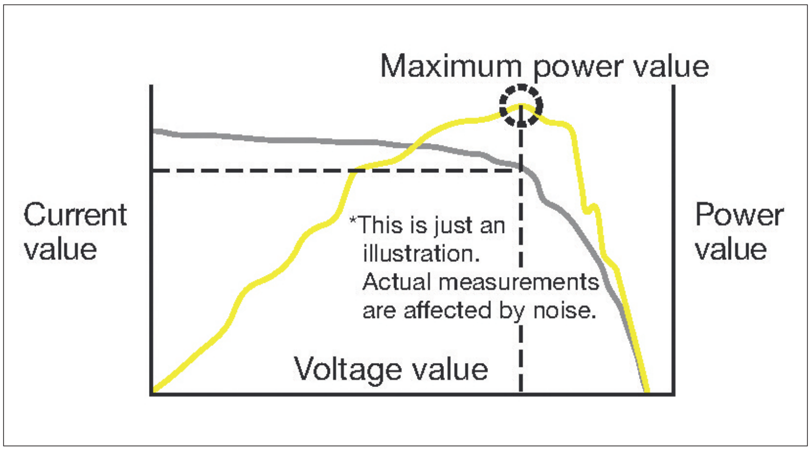



**Figure 5: Modern drive systems with integrated inverters do not allow access to the AC signals. Here one of the main measurement tasks is to measure the overall drive train efficiency from DC to mechanical power. The example shows 4 DC measurements (1 to 4) with the corresponding 4 mechanical power measurements (M1 to M4)**




LEFT Figure 6: **Typical voltage, current, and power measurements in MPPT control**


BELOW Figure 7: **In transformer or reactor development, the WT5000 can be used to evaluate magnetic material characteristics using Epstein frame system**

the ability to measure harmonics up to the 500th order even at low rotation speeds, the WT5000 supports harmonic analysis without the need for an external sampling clock.

## Renewable energy development

Energy generated by photovoltaic cell modules and wind turbines is converted from DC to AC by a power conditioner. Minimizing losses in these conversions is key to improve the efficiency of the overall energy system.

Key requirements for this application are:

- Multi-phase measurements from boost converter, inverter and storage battery
- Evaluation of maximum power and instantaneous peak values
- Energy bought and sold in grid
- Battery charging/discharging characteristics
- Harmonic analysis of inverter signals at various generator speeds

Multi-channel power measurements evaluate power conditioner efficiency with simultaneous measurements from the inputs and outputs of boost converter, inverter, and storage battery. With measurement capabilities from up to 7 input elements the WT5000 is ideal for voltage, current, power, and frequency (for AC) before and after each converter, as well as converter efficiency and charging efficiency.

In photovoltaic power generation, an Maximum Power Point Traker (MPPT) controller varies the voltage to maximize energy harvested from the solar panel. The WT5000 is capable of measuring not only the voltage, current, and power but also the voltage, current, and power peak values plus (+) and minus (–) sides, respectively (Figure 6).

For Energy Bought/Sold and Charged/Discharged the WT5000E provides a current integration (q), apparent power integration (WS), reactive power integration (WQ), as well as effective power integration capable of integration in the power sold/bought and charge/discharge modes.

Harmonics Analysis & comparisons are accomplished by voltage fluctuations and harmonics flow into the power systems due to reverse power flow. The harmonic measurement function enables measurement of harmonic components to compute and display total harmonic distortion (THD) and harmonic distortion factor.



## Magnetic characteristics testing

In transformer or reactor development, the WT5000 can be used to evaluate magnetic material characteristics using Epstein frame system.

Key requirements include:

- High precision measurements of primary coil current and secondary coil voltage is needed
- High accuracy in low power factor is needed
- The magnetic flux density B and AC magnetic field H are key parameters to calculate iron loss

Here WT5000 provides power accuracy of 0.01 % of reading + 0.02 % of range (50/60 Hz). Effect of Power Factor is
0.02 % of S (0.5 A or more) and 0.07 % of S (200 mA or less).

For customers who use a large number of power meters, WT5000 can be used as a reference standard for periodic in-house calibration of power measurement instruments, such as the WT300E series and WT500.

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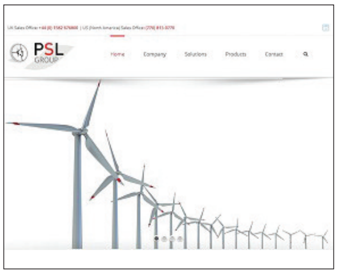

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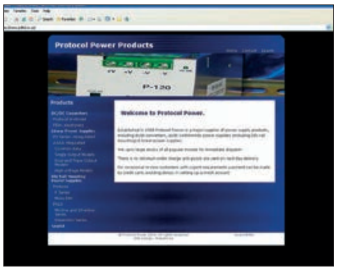


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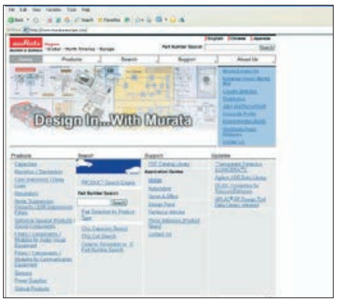


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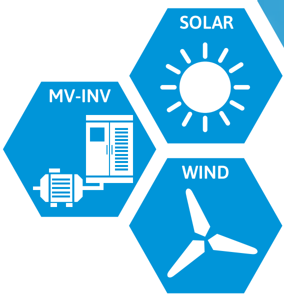


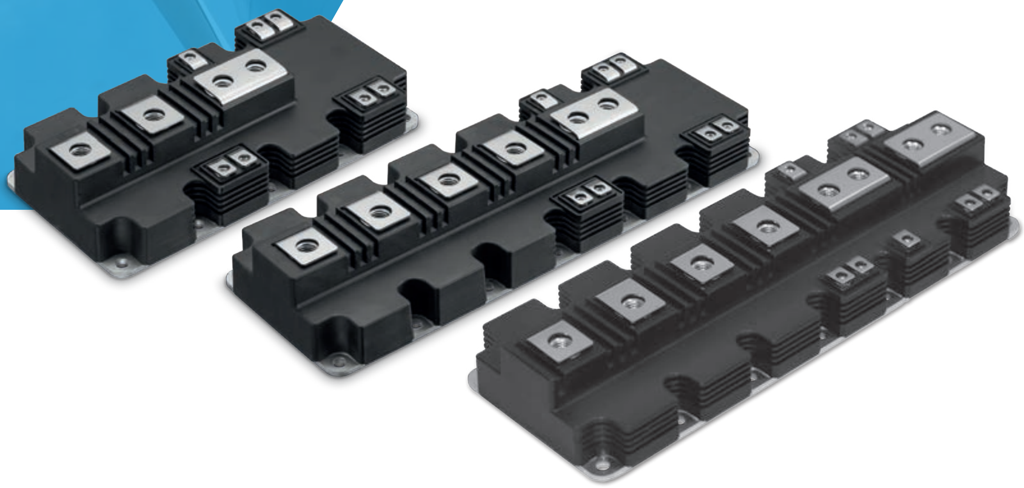

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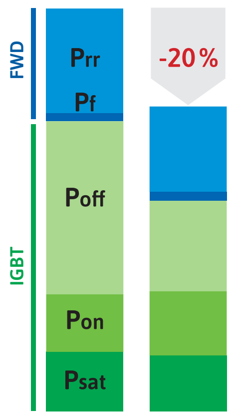


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