POWER ELECTRONICS EUROPE

ISSUE 3 – June/July 2017 www.power-mag.com

SILICON CARBIDE

CoolSiC Trench MOSFET Combining SiC Performance With Silicon Ruggedness

THE EUROPEAN JOURNAL FOR POWER ELECTRONICS AND TECHNOLOGY

Also inside this issue

Editor Achim Scharf
Tel: +49 (0)892865 9794
Fax: +49 (0)892800 132
Email: achimscharf@aol.com

Production Editor Chris Davis
Tel: +44 (0)1732 370340

Financial Manager Clare Jackson
Tel: +44 (0)1732 370340
Fax: +44 (0)1732 360034

Reader/Circulation Enquiries
Perception-MPS Ltd.
Tel: +44 (0) 333 577 9202
Email: dfamedia@pmps.info

INTERNATIONAL SALES OFFICES
Mainland Europe:
Victoria Hufmann, Norbert Hufmann
Tel: +49 911 9397 643 Fax: +49 911 9397 6459
Email: pee@hufmann.info

Armin Wezel
phone: +49 (0)30 52689192
mobile: +49 (0)172 767 8499
Email: armin@eurokom-media.d

Eastern US
Karen C Smith-Kernc
email: KarenKCS@aol.com
Western US and Canada
Alan A Kernc
Tel: +1 717 397 7100
Fax: +1 717 397 7800
email: AlanKCS@aol.com

Italy
Ferruccio Silvera
Tel: +39 022 846 716 Email: ferruccio@silvera.it

Japan:
Yoshinori Ikeda,
Pacific Business Inc
Tel: 81-(0)3-3661-6138
Fax: 81-(0)3-3661-6139
Email: pbi2010@gol.com

Taiwan
Prisco Ind. Service Corp.
Tel: 886 2 2322 5266 Fax: 886 2 2322 2205

Publisher & UK Sales Ian Atkinson
Tel: +44 (0)1732 370340
Fax: +44 (0)1732 360034
Email: ian@dfamedia.co.uk
www.power-mag.com

Circulation and subscription: **Power Electronics Europe** is available for the following subscription charges. **Power Electronics Europe**: annual charge UK/NI £95, overseas $160, EUR 150.
Contact: DFA Media, 192 The High Street, Tonbridge, Kent TN9 1BE Great Britain.
Tel: +44 (0)1732 370340.
Fax: +44 (0)1732 360034. Refunds on cancelled subscriptions will only be provided at the Publisher's discretion, unless specifically guaranteed within the terms of subscription offer.

Editorial information should be sent to The Editor, **Power Electronics Europe**, PO Box 340131, 80098 Munich, Germany.

Printed by: Garnett Dickinson.

ISSN 1748-3530

COVER STORY

CoolSiC Trench MOSFET Combining SiC Performance With Silicon Ruggedness

This article summarizes selected features of the new ColSiC™ MOSFET. The device combines low static and dynamic losses with high Si-IGBT like gate oxide reliability right fitting to typical industrial requirements. The temperature behavior, threshold voltage selection and Vgs_on makes the device easy to operate, in particular for operation in parallel. The switching behavior can be fully controlled by the gate resistor. SiC MOSFETs based power switches offer significant system advantages in terms of power density, efficiency and cooling effort due to their much lower losses compared to Si-IGBT. It is shown that the system costs of solar applications as well as the running costs of UPS systems can be drastically reduced despite the more expensive semiconductor component. Thus, the technology is ready to penetrate more and more applications in the coming years. Easy 1B is first full-SiC power module based on the 1200 V CoolSiC MOSFET family. Easy 1B with B6 (Six-Pack) topology features an on-resistance of 45 mΩ. The body diode works as a low-loss freewheeling function. Easy 1B is suitable for drives, solar or welding applications.
More details on page 25.

Cover image supplied by Infineon Technologies AG, Neubiberg, Germany

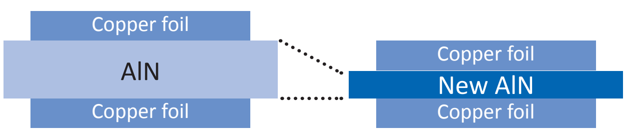
Fuji X-Series 6 in 1 & PIM

with high performance AlN DCB

MAIN FEATURES

- **Improved switching performance**
- **Reduced on-state voltage**
- **Enhanced power cycling capability**
- **Increased output power**
- **Tj(op), max = 175 °C**

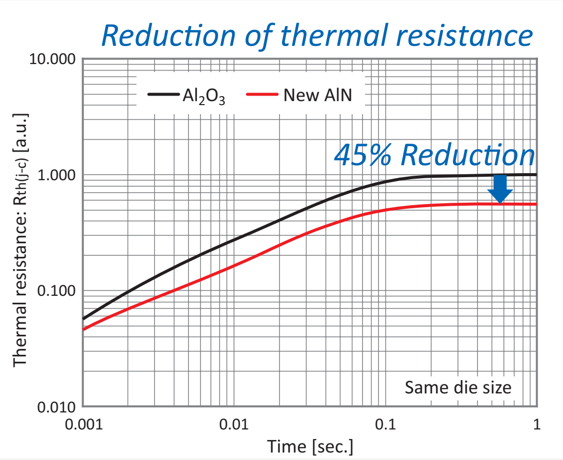
CROSS-SECTION STRUCTURE OF SUBSTRATE

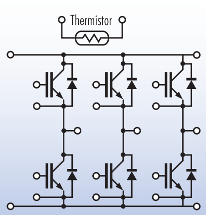
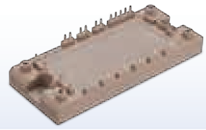
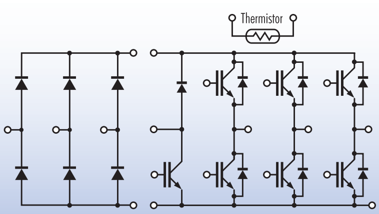
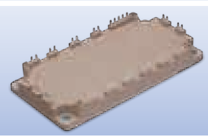


Conventional AlN substrate — New thinner AlN substrate

NEW THIN AlN SUBSTRATE

- **Improved thermal cycling capability**
- **Rth(j-c) was reduced by 45 %**



Line-up Plan 1200 V				
	6 in 1	EP2 & EP3	PIM	
	100 A		75 A	
	200 A		150 A	

Fuji Electric
Innovating Energy Technology

Fuji Electric Europe GmbH
Goethering 58
63067 Offenbach/Main – Germany

Fon +49(0)69 - 66 90 29 0
info.semi@fujielectric-europe.com
www.fujielectric-europe.com

The Way Towards Applications

The power electronics market is influenced heavily by the discrete/module power semiconductor market, which is estimated of around $17 billion in 2017 by market researcher Yole, in the year 2020 an increase up to $21 billion is expected. Today is the starting point of replacing Silicon MOSFETs and IGBTs with SiC and GaN devices. The voltage range 600 – 900 V will become the battlefield SiC versus GaN. GaN devices rated at 600 V have passed the so-called hype cycle and are going now into applications. Over time pricing of GaN at component level will be lower than Silicon, On Semiconductor expects by 2022 a crossing with SJ MOSFETs. Thus GaN has the opportunity to become mainstream, but it will take up to ten or more years. Regarding applications travel adapters are a good starting point for GaN, automotive will follow sometimes.

With SiC the way is open to unipolar concepts above 1200 V. SiC allows for higher switching frequencies even in the megahertz range, but also on lower switching frequencies can be better controlled and have lower switching losses due to the absence of tail current observed in IGBTs. SiC technology enables vertical structures within the devices, whereas in GaN on Silicon only lateral structures are possible – but with the advantage of better integration.

Continued advances in diameter expansion, volume, quality, and cost of SiC bulk wafers has reached a point where high-volume 150 mm fabrication facilities can utilize SiC wafers (see our SiC MOSFET feature). At Wolfspeed, nearly 18 metric tons of 150 mm SiC wafers were shipped in calendar year 2016 to support markets such as LED, RF, and power, with continued growth forecast for 2017 and beyond. 200 mm diameter SiC wafers have also recently been demonstrated in R&D, as continued wafer diameter expansion development continues. The quality of the SiC wafers has also improved consistently over the years, with median micropipe defect density falling to 0.2 /cm? in 2016, enabling large area SiC MOSFETs to be fabricated with high-yield, and meeting automotive AEC-Q-101 qualification. Not only Wolfspeed are offering SiC MOSFETs (see our PCIM review), new entrants such as Littelfuse are competing with established companies such as Infineon. Their new CoolSiC device, a 1200 V SiC trench MOSFET, use the the intrinsic body diode along with the conduction channel as freewheeling diode, thus in new power modules no antiparalleled diode is necessary (see our cover story).

As an application example, at Siemens a dual three-phase 3-level inverter (2 x 27 kW; input 600 VDC; output 2 x 400 VAC 45 A) has been realized with the latest generation of planar SiC-MOSFETs, a space saving embedding technology of power semiconductors, an optimized air cooling concept and a novel DC link configuration. The inverter has a high power density of 17,2 kW/l combined with an efficiency of 99,2 percent. With the new design the volume could be reduced by a factor of six in comparison to a standard high-performance Si-based converter. These features convinced the PCIM award committee to give the Best Paper Award (Euro 1000.00 and Invitation to PCIM Asia 2018), co-sponsored by Power Electronics Euope) to the paper "Air Cooled SiC Three Level Inverter with High Power Density for Industrial Applications". The proposed inverter design and the latest generation of 1200V SiC-MOSFETs lead to a very compact air cooled inverter for industrial applications. Additionally, an improved performance regarding the switching frequency was shown. Crucial for fast switching SiC devices is the low inductive design of the switching cell. The used embedding technology of the power devices into the PCB shows a possible solution to enable higher function integration combined with a low inductive design. The optimized cooling design keeps the PCB temperature relatively low - in an acceptable range for standard lead-free soldering capable FR4 materials and other used devices, placed on the PCB near to the power devices. With the DC link design inside the housing, a space-saving solution with high capacitance, suitable for industrial applications can be realized (more in our PCIM review).

However, this does not necessarily mean doom for Silicon power MOSFETs. Looking back at the development of bipolar transistors and power MOSFETs in the past 20 years in different applications, there will still be a very solid market share reserved for Silicon power MOSFETs. Both SiC and GaN devices will penetrate the high frequency market, but the majority of the market will still use Silicon power MOSFETs, thanks to their proven reliability and good cost performance ratio, according to market researcher.

Achim Scharf
PEE Editor

Stable Growth In Power Semiconductor Markets

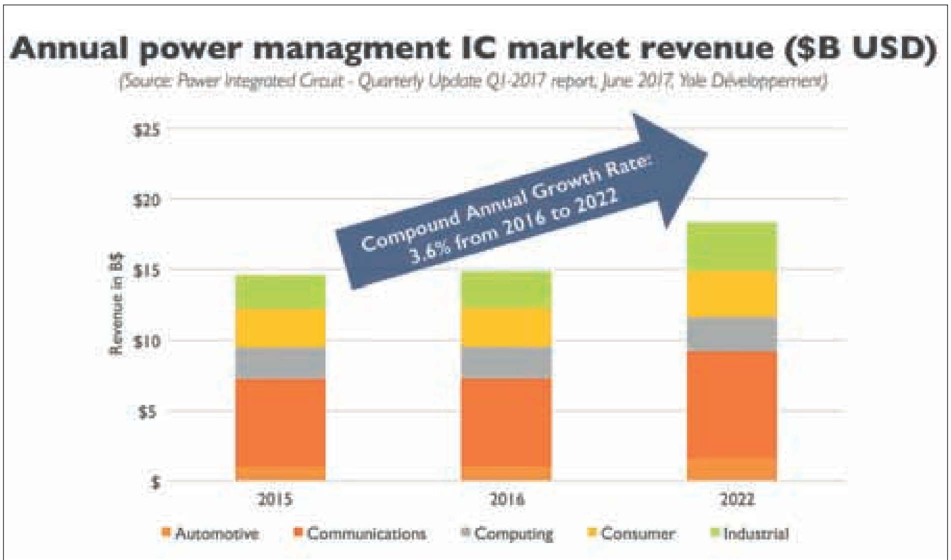
The power management IC market revenue will reach $18 billion in the year 2022, expects Yole Développement as an outcome from its new global market research database titled, Power Integrated Circuit 2017 - Quarterly Update. The market research company forecasts, power ICs market segment will benefit from multiple key end markets and deliver a 3.6 % CAGR between 2016 and 2022.

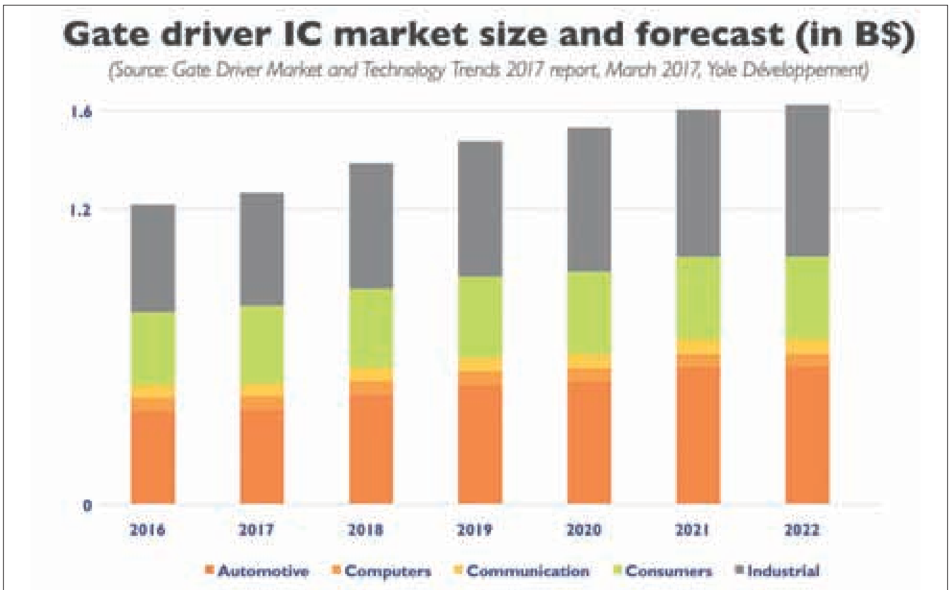
This market evolution is in line with the general health of the overall semiconductor industry, comments Yole's analyst Jonathan Liao. This new database is also analyzing the market positioning of key power IC players such as Alpha and Omega Semiconductor, Analog Devices, Dialog Semiconductor, Diodes, Fuji Electric, Infineon Technologies, Intersil, IXYS, Linear Technology, Lite-On Semiconductor, MagnaChip, Maxim Integrated, MediaTek, Microchip and more.

Isolation via gate drivers

Gate driver ICs will deliver a 6.1 % CAGR from 2017-2022. The gate driver IC market revenue was estimated to have been $1.2 billion in 2016.

Most of power MOSFETs and IGBTs are driven by gate drivers IC. However, while almost all IGBTs require a gate driver, MOSFETs are showing a considerably lower usage of gate driver ICs. Gate driver ICs utilization varies on voltage and power levels and it strongly depends on the applications. According to Yole's analysts, in 2016, more than 60 % of the gate drivers IC market correspond to the ones combined with MOSFETs. But this figure step by step decreases slowly and appear to be stabilizing. In parallel IGBT market share increases. As a consequence, the revenue gap between MOSFET and IGBT gate drivers will be quickly narrowing in a near future. "Usage of single channel and half bridge gate driver ICs will increase over the next few years due to the need for isolation integration", explains Liao. "Half bridge gate driver ICs are estimated to have accounted for over 40 % of gate driver revenues in 2016. Single side gate driver ICs were the second most popular topology with about 30 % of revenue. While full bridge and three phase gate drivers are mostly found in motor control and inverter applications for low-mid power."



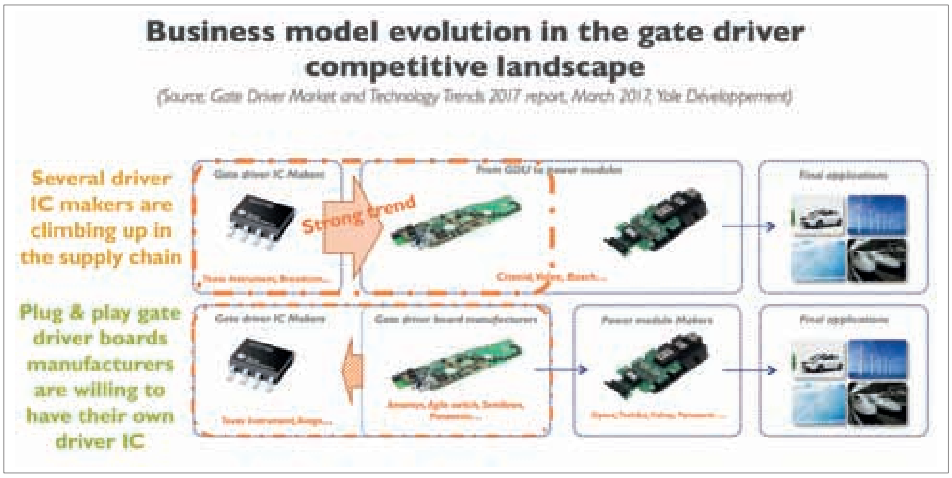


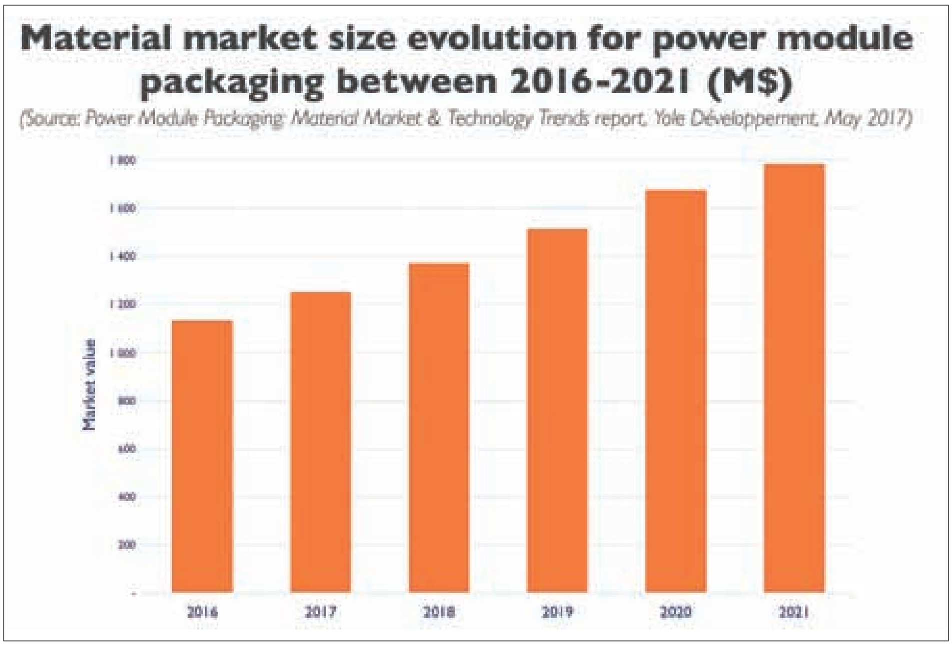
From a technology point of view, new requirements related to isolation or the use of GaN and SiC power transistors demand advanced driver IC technologies to be developed. Over recent years, all major players have started providing isolation-integrated products, the coreless transformer being the main type. Besides isolation technologies, niche applications such as high temperature operation and other harsh environment requirements provide additional growth opportunities for gate drivers. SiC-based power switches can endure high temperature environments with the material's high Tj and Te performance characteristics. Companies such as Cissoid and X-Rel Semiconductor are looking to capitalize on the potential of SiC in these niche applications. GaN FETs can switch at a much higher frequency than Silicon-based MOSFETs. Higher frequency provides advantages but also challenges. A case study of Navitas, incorporating a GaN FET with GaN drivers on the same substrate, shows the level of involvement of several GaN and SiC players, in order to get adequate drivers to facilitate the use of wide band gap devices in the new generation of converters.

Power modules go automotive

In 2016, the power module market was worth almost $3.2 billion and from there it will grow steadily for the next five years. Industrial applications remain the biggest part of the power module market. However, EV/HEV market, with its double-digit growth forecast for the period 2016-2021, will represent around 40 % of this market by 2021. Moreover, the automotive industry is leading in technological innovations in packaging, helping and accelerating the implementation of these new technologies thanks to high manufacturing volumes.

In recent years, some consolidations among





power semiconductor market leaders took place, with several acquisitions, such as Infineon Technologies buying International Rectifier and ON Semiconductor buying Fairchild. These moves were intended to strengthen positions in the overall power semiconductor business.

Nevertheless, in coming years the market leaders will face strong competition from Tier-1 automotive manufacturers such as Denso or Robert Bosch and new entrants from China such as Starpower and CRRC. "The power module market is becoming extremely competitive with several new players arriving from different directions", asserts Milan Rosina, Senior Analyst for Energy Conversion & Emerging Materials.

A large part of the power module cost is dedicated to raw materials for packaging - materials for die-attach, substrate-attach, substrate, baseplate, encapsulation, interconnections and casings already constitute a $1.1 billion market in 2016 and Yole expects a steady growth until 2021. "To understand the evolution of the power packaging market, it is now essential to look in details the selected materials and design and evaluate each innovation", comments Mattin Grao Txapartegi, Technology & Market Analyst, Power Electronics. "Yet the growth will not be even across all raw material markets. Die-attach materials have the highest forecast CAGR for 2016-2021, at over 13 %. Casings and encapsulation have the lowest CAGR, at 5-7 % for 2016-2021. The main differences arise from technology choices for those materials and their impact on the each market segment. For instance, the greater presence of epoxy resin will reduce the cost of encapsulation in power modules. Substrates and baseplates account for half of the packaging raw material market, and together are worth over $550 million. Therefore, the choice of technology in ceramic substrates or baseplates can have a great impact on final power module cost. Around 25 % of the cost is related to die-attach or substrate attach material. Rest of the cost is divided between encapsulation, interconnections and the casing."

www.yole.fr

Stable Market Conditions For Industrial Semiconductors

Worldwide industrial semiconductor revenues grew by 3.8 % year-over-year in 2016, to $43.5 billion, according to the latest June analysis from business information provider IHS Markit.

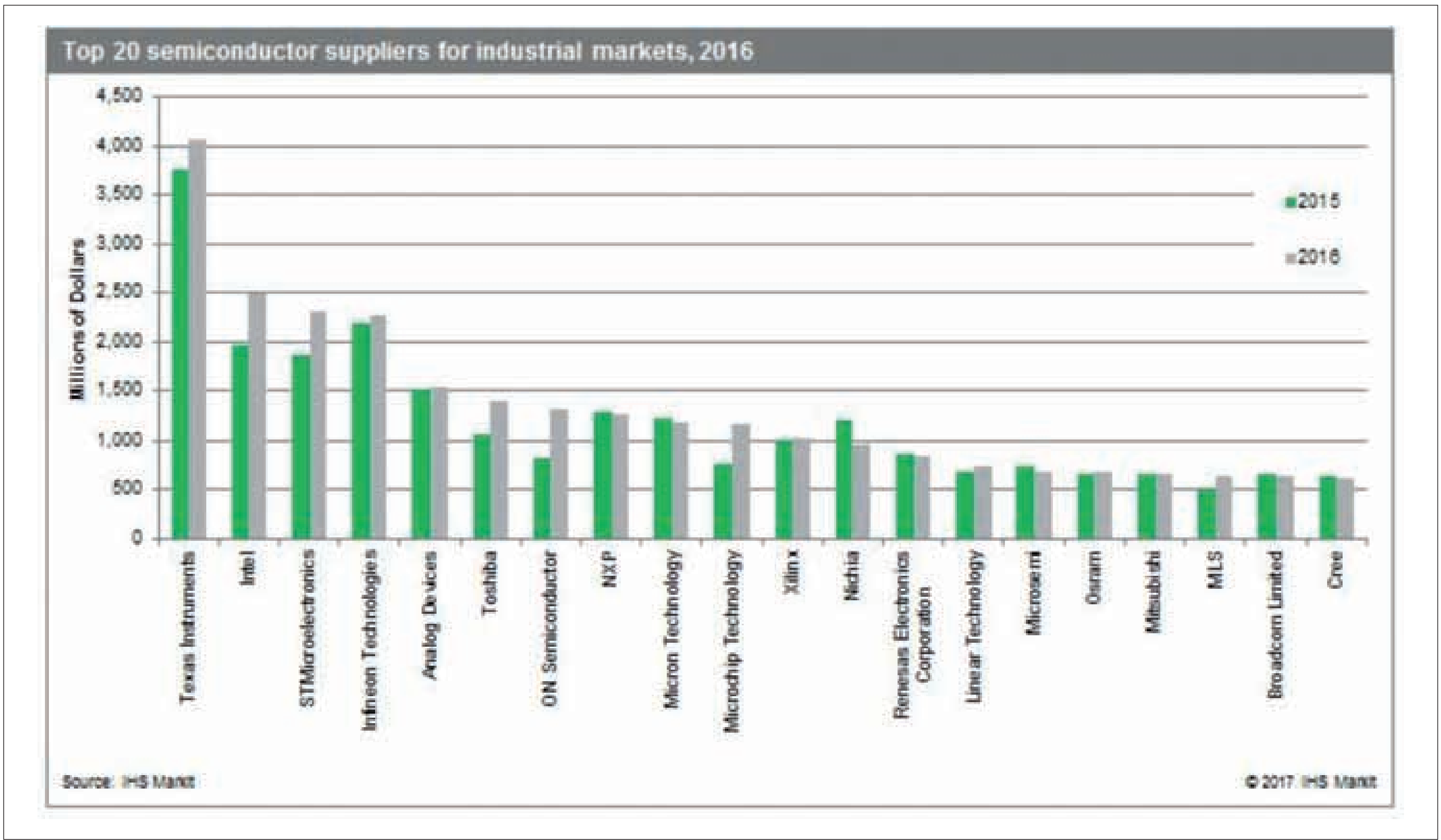
Industrial electronics equipment demand was broad-based, with continued growth in commercial and military avionics, digital signage, network video surveillance, HVAC, smart meters, traction, PV inverters, LED lighting and various medical electronics such as cardiac equipment, hearing aids and imaging systems. The U.S. economy continued to boost industrial spending while improved economic conditions in Europe and large emerging countries like China, India and Brazil toward the end of 2016 that propelled growth. These economic conditions are expected to continue thorough 2017, according to the IHS Markit analysis.

Texas Instruments (TI) maintained its position as the largest industrial semiconductor supplier in 2016 followed by Intel, STMicroelectronics, Infineon Technologies and Analog Devices. Intel surged to second place, swapping spots with Infineon, which dropped to fourth. The Intel IoT group's double-digit revenue growth is attributed to strength in factory automation, video surveillance and medical segments. "Toshiba, ON Semiconductor and Microchip Technology climbed into the top 10 industrial semiconductor supplier ranks in 2016," said Robbie Galoso, principal analyst, industrial semiconductors for IHS Markit. Toshiba's industrial market share rank jumped to number six, according to survey feedback. Toshiba's industrial electronics revenue grew from $1.1 billion in 2015 to $1.4 billion in 2016 - a 30.5 % bounce driven by discretes, ICs, memory and logic IC solutions in manufacturing and process automation, power and energy as well as security and video surveillance.

Mergers and acquisitions make an impact

The semiconductor industry had another cycle of merger and acquisition in 2016 that affected the competitive landscape. The combined ON Semiconductor - Fairchild organization generated $1.3 billion in 2016 industrial revenues, catapulting the consolidated company into seventh place. The acquisition of Fairchild allowed On Semiconductor to leapfrog to the top ranks of the power discrete market, forecast to be one of the higher growth markets over the next five years. On Semiconductor has been a relatively small player in the power discrete segment; with the Fairchild acquisition, it now has the scale and product portfolio to compete effectively with the combined Infineon International Rectifier. On Semiconductor's 2016 revenue grew nearly 60 %, largely driven by analog and discretes in the manufacturing and process automation and the power and energy sectors, both of which were sizeable segments for Fairchild.

The Microchip Technology – Atmel merger generated $1.2 billion in revenues in 2016, propelling the combined company into 10th place. The acquisition of leading microcontroller supplier, Atmel, positioned Microchip as the third-ranked supplier of microcomponent ICs in the industrial market, after Intel and TI. The combination of



Microchip and Atmel created an MCU powerhouse, allowing it to compete effectively against the combined NXP Freescale. Microchip Technology's 2016 revenue growth of 53 % was driven by microcomponent ICs in manufacturing and process automation, Atmel's bread and butter. Toshiba, Micron and ON Semiconductor displaced Nichia, Renesas and Xilinx in the top 10 rankings.

China's massive investments in light-emitting diode (LED) manufacturing capacity propelled Chinese firm MLS into the 2016 top 20 industrial semiconductor supplier ranks, displacing Maxim. "MLS posted revenue growth of 27 %, to $640 million, building its share against competition including top-20 firms Nichia, Osram and Cree," added Galoso.

Strategic acquisitions will continue to play a major role in shaping the overall semiconductor market rankings in key industrial semiconductor segments. IHS Markit expects Analog Devices to increase its lead in 2017 market shares among the top semiconductor suppliers, due to an acquisition of Linear Technology. A joint Analog Devices - Linear Technology would battle for the number four spot and impressive gains in test and measurement, manufacturing and process automation as well as medical electronics. Among the top 10 semiconductor suppliers, eight companies achieved growth in 2016, with two companies posting double-digit growth due to mergers.

Industrial semiconductor key growth drivers

Optical semiconductors delivered solid performance, driven by continued strength in the LED lighting market. IHS Markit expects the LED segment to grow from $9.4 billion in 2016 to $14.5 billion in 2021. With many countries phasing out incandescent bulbs, mass adoption of energy-efficient LED lighting solutions will continue to gain traction as prices for LED lamps fall to affordable levels for average-income households. Discrete power transistors, thyristors, rectifiers and power diodes are expected grow from $5.7 billion in 2015 to $8 billion in 2021 due to policy shifts toward energy efficiency in the factory automation market. IHS Markit projects that the microcontrollers (MCUs) segment will grow robustly in the long term, expanding from $4.4 billion in 2016 to $7 billion in 2021, attributing this growth to both shipments and average selling price driven by system level cost savings provided by MCUs through advances in power efficiency and integration integrated features supporting connectivity, security, sensors and HMI.

www.ihsmarkit.com

Battery Improvements Spark HEV/EV Market Breakthrough

Advances in battery technology are challenging automakers and their suppliers to meet higher market demand for hybrid and electric vehicles without compromising quality, also advances in electric motors, as pointed out at CWIEME from June 20 – 22 in Berlin.

2017 marks the 20th anniversary of the Toyota Prius, the world's first widely-available hybrid electric vehicle (HEV). Since then more than 12 million HEVs have been sold around the world. Yet sales of HEVs and their full-electric counterparts still account for only a relatively small proportion of the global car market. Thanks to recent advances in battery technology, however, this is all about to change. "Aside from charging infrastructures, battery cost and life have proved the greatest obstacles to growth in the HEV/EV market so far. It's definitely not the electric motor or power electronics that are holding back the pace of the industry," said Professor David Greenwood, head of advanced propulsion systems at WMG of the University of Warwick, in a keynote speech at CWIEME Berlin – the world's leading exhibition for coil winding, electric motor and transformer manufacturing technologies. Professor David Greenwood leads the advanced population systems team at WMG with a focus on energy storage (battery systems), energy conversion (electric machines and power electronics) and energy management.

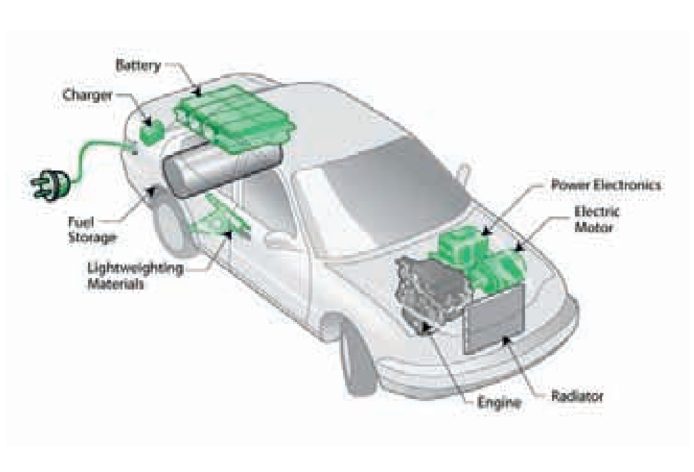
Battery costs for HEVs and EVs can be as much as two to three times greater than the motor and power electronics combined. However, they have decreased significantly over the last eight years; meanwhile energy density has almost doubled. These advances can be attributed to improved electrochemistry and packaging of the electrochemistry, as well as economies of scale. "It's the speed at which we can improve the battery that will ultimately impact sales and usage of HEVs and EVs," Greenwood continues.

"Right now battery performance is increasing on a fast trajectory but to get to a point where HEVs and EVs are fully democratised and make up 60-70 % of all sales, we need to double the energy density again."

Current research into making this leap is investigating the use of silicone and lithium anodes and different ways of structuring electrodes. Further research on sodium-ion chemistries could yield significant cost benefits, as well as different ways of packaging the cells into modules.

New opportunities for the coil winding community

The growth of the HEV and EV market is good news not only for the automotive industry but all involved in the business of coil winding. "HEV and EVs are now starting to account for four to five percent of all vehicle sales in some months, which means we are no longer just selling to early adopters but to real customers. This is the point at which volumes can really change, opening up supply chain opportunities for a whole range of organizations, who perhaps weren't selling to the automotive industry before but now could – if they can design their products and services to meet the cost, volume and quality requirements of that market," Greenwood explained.



As the market continues to take off in line with battery technology, automakers will need to adapt motor designs to suit higher volume production. One way is by selecting windings that permit a high degree of manufacturing automation. OEMs will also need to analyse manufacturing processes to ensure high quality. "There are plenty of manufacturers out there that are able to produce electric motors in high volumes but the challenge is meeting automotive levels of quality," Greenwood comments. Certain ways of cutting laminated steels, for example, are known to negatively affect their magnetic properties, which reduces the efficiency of the electric machine. "It's not just about designing a good machine but designing one that when mass-produced still delivers on its original promise," he adds.

Advances in electrical steel production technology

While widespread smart factories may be a few years away, Stefano Cicale, project leader at Rina Consulting, reported in a CWIEME seminar that new production processes are significantly improving the performance of electrical steels. Instead of reheating the slab at high temperature, ammonia is injected in the final stages of decarburization annealing to induce nitrides precipitation. This enables higher control over the secondary recrystallization and, therefore, the production of thinner grades of electrical steels with the lower losses demanded by high frequency applications.

"Until a few years ago, the minimum thickness available for electrical steel was 0.35mm. Today, 0.20mm or even lower is possible," Cicale said. Cicale also commented on the increased use of laser scribing techniques to artificially reduce electrical steel grain size and improve magnetic characteristics.

www.coilwindingexpo.com/berlin

SCALE-iDriver IC Family Supports Now 1700 V IGBTs

Power Integrations' new devices support IGBT blocking voltages up to 1700 V, which are generally used in 400 VAC and 690 VAC line applications. They are also suited for the latest three-level topology photovoltaic inverters and for photovoltaic arrays leveraging the new 1500 V DC bus standard.

1700 V SCALE-iDriver ICs, optimized for driving both IGBTs and MOSFETs, combine FluxLink™ magneto-inductive bi-directional communications technology with its SCALE™ power device driver technology. FluxLink eliminates the need for opto-electronics and the associated compensation circuitry, and SCALE technology incorporates all key gate driver functions into an ASIC. Additionally eSOP package features greater than 9.5 mm of creepage and a CTI of 600, ensuring substantial operating voltage margin and high system reliability.

The status of the power semiconductor switch and SCALE-iDriver is monitored via the SO pin. Command signals are transferred from the primary (IN) to secondary-side via FluxLink isolation technology. The GH pin supplies a positive gate voltage and charges the power semiconductor gate during the turn-on process. The GL pin supplies the negative voltage and discharges the gate during the turn-off process.

Short-circuit protection is implemented using a desaturation detection technique monitored via the VCE pin. After the SCALE-iDriver detects a short-circuit, the semiconductor turn-off process is implemented using an Advanced Soft Shut Down (ASSD) technique. The ICs can be operated from -40°C to +125°C and at frequencies of up to 75 kHz. The family meets the upcoming requirements of IEC 60747-17 and VDE 0884-17.

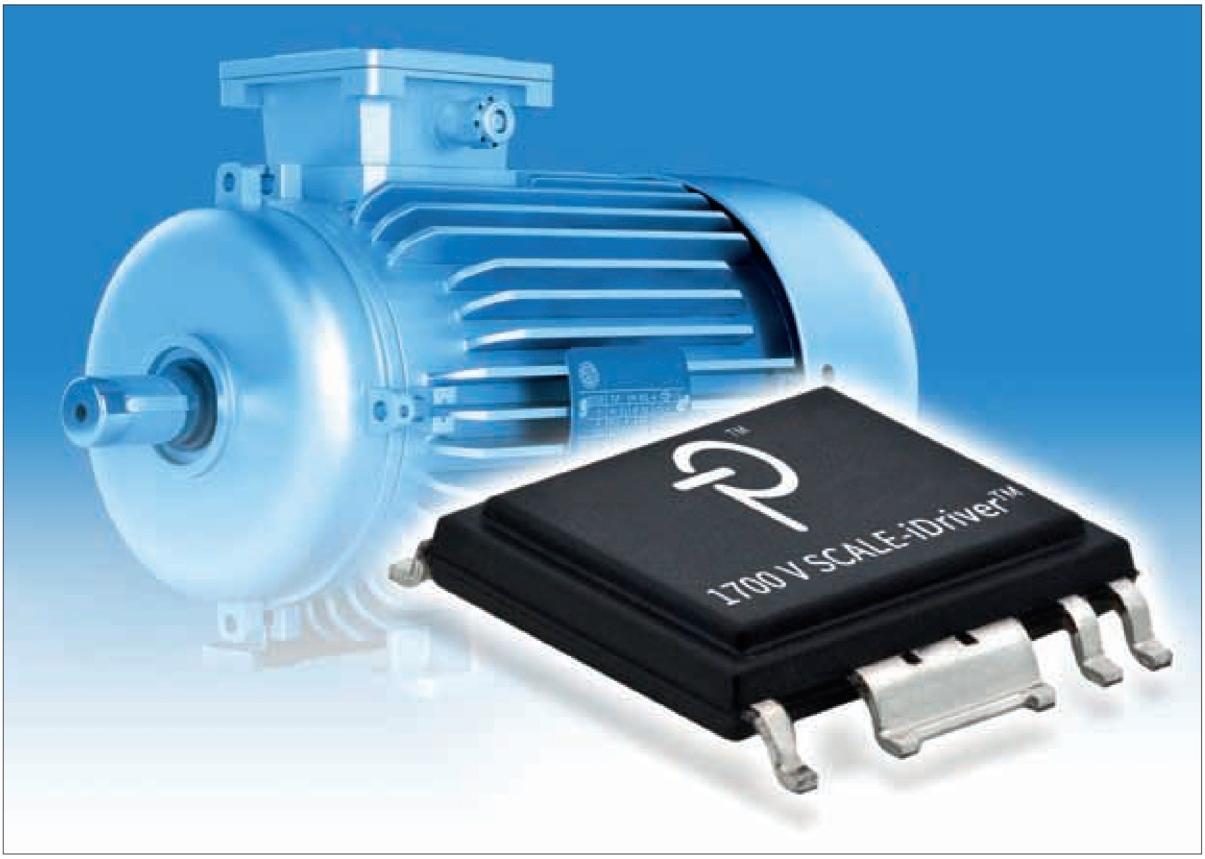
1700 V SCALE-iDriver ICs deliver a gate current of up to 8 A and support systems of over 110 kW without an external booster, or up to 30 A gate current and over 400 kW with an external booster in applications such as industrial drives, power supplies/UPS, photovoltaic inverters of all sizes, industrial HVAC, EV charging and traction equipment including commercial EVs.

Application example

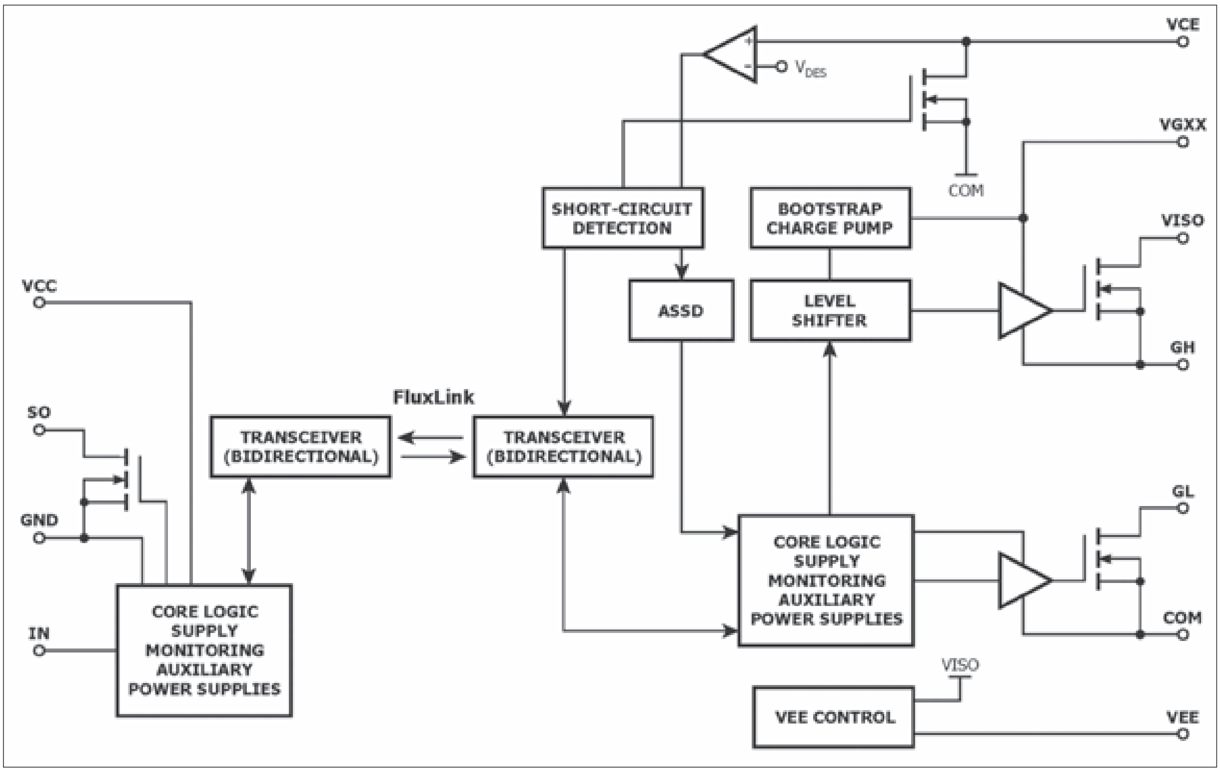
In a typical SID1183K design, the primary-side supply voltage (V_{VCC}) is connected between VCC and GND pins and supported through a supply bypass ceramic capacitor C_1 (4.7 µF typically). If the command signal voltage level is higher than the rated IN pin voltage (in this case 15 V) a resistive voltage divider should be used. Additional capacitor CF and Schmitt trigger IC_1 can be used to provide input signal filtering. The SO output has 5 V logic and the R_{SO} is selected so that it does not exceed absolute maximum rated I_{SO} current.

The secondary-side isolated power supply (V_{TOT}) is connected between VISO and COM. The positive voltage rail (V_{VISO}) is supported through 4.7 µF ceramic capacitors CS21 and CS22 connected in parallel. The negative voltage rail (V_{VEE}) is similarly supported through capacitors CS11 and CS12. The gate charge will vary according to the type of power semiconductor switch that is being driven. Typically, C_{S11} + C_{S12} should be at least 3 µF multiplied by the total gate charge of the power semiconductor switch (Q_{GATE}) divided by 1 µC. A 10 nF capacitor C_{GXX} is connected between the GH and VGXX pins.

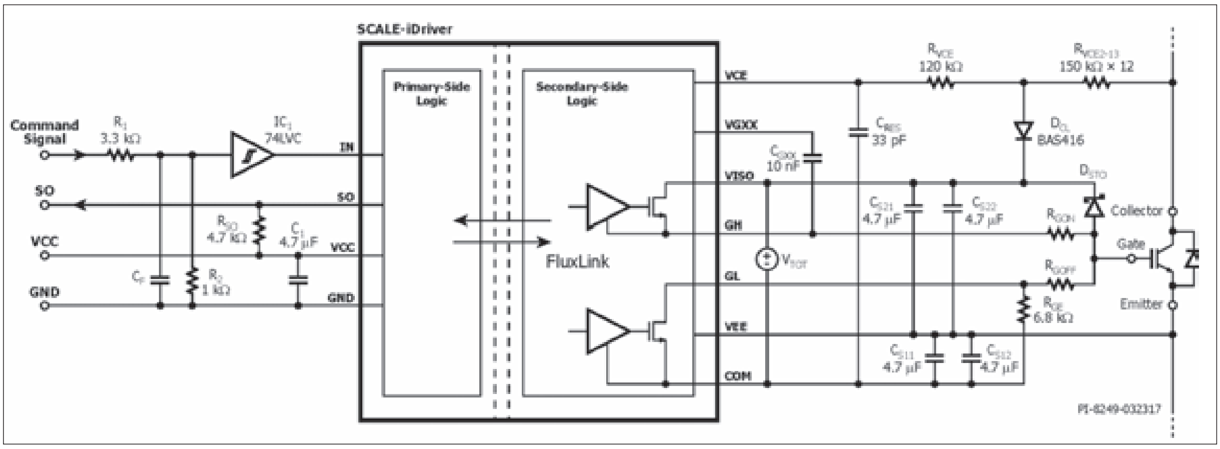
The gate of the power semiconductor switch is connected through resistor R_{GON} to the GH pin and by R_{GOFF} to the GL pin. If the value of R_{GON} is the same as R_{GOFF} the GH pin can be connected to the GL pin and a common gate resistor can be connected to the gate. In each case, proper consideration needs to be given to the power dissipation and temperature performance of the gate resistors. To ensure gate voltage stabilization and collector current limitation during a short-circuit, the gate is connected to the VISO pin through a Schottky diode D_{STO} (for example PMEG4010). To avoid parasitic power-



1700 V SCALE-iDriver ICs, optimized for driving both IGBTs and MOSFETs



1700 V SCALE-iDriver IC functional block diagram



SCALE-iDriver application example using a resistor network for desaturation detection

switch-conduction during system power-on, the gate is connected to COM through 6.8 kΩ resistor.

The switch desaturation can be measured using resistors RV$_{CE2}$ – R$_{VCE13}$. In this example all the resistors have a value of 150 kΩ and 1206 size. The total resistance is 1.8 MΩ. The resistors should be chosen to limit current to between 0.6 mA to 0.8 mA at maximum DC-link voltage. The sum of R$_{VCE2}$ – RV$_{CE13}$ should be typically 1.8 MΩ for 1700 V semiconductors. In each case the resistor string must provide sufficient creepage and clearance distances between collector of the power semiconductor and SCALE-iDriver. The low leakage diode DCL keeps the short-circuit duration constant over a wide DC-link voltage range.

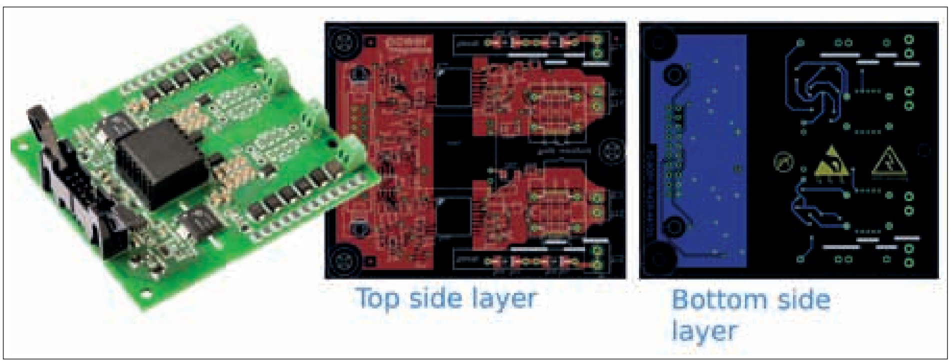
Response time is set up through RVCE and CRES (typically 120 kΩ and 33 pF respectively for 1700 V semiconductors). If short-circuit detection proves to be too sensitive, the C$_{RES}$ value can be increased. The maximum short-circuit duration must be limited to the maximum value given in the power semiconductor data sheet.

The recommended PCB layout is a two layer design. It is important to ensure that PCB traces do not cover the area below the desaturation resistors or diodes. This is a critical design requirement to avoid coupling capacitance with the SCALE-iDriver's VCE pin and isolation issues within the PCB.

Gate resistors are located physically close to the power semiconductor switch. As these components can get hot, it is recommended that they are placed away from the SCALE-iDriver.

SID1183K devices are available now priced at $3.19 in 10,000-piece quantities. More details under

https://www.power.com/products/1700-v-scale-idriver.



Top and bottom view of recommended PCB layout. Simple two layer PCB replaces the multi-layer PCBs required today

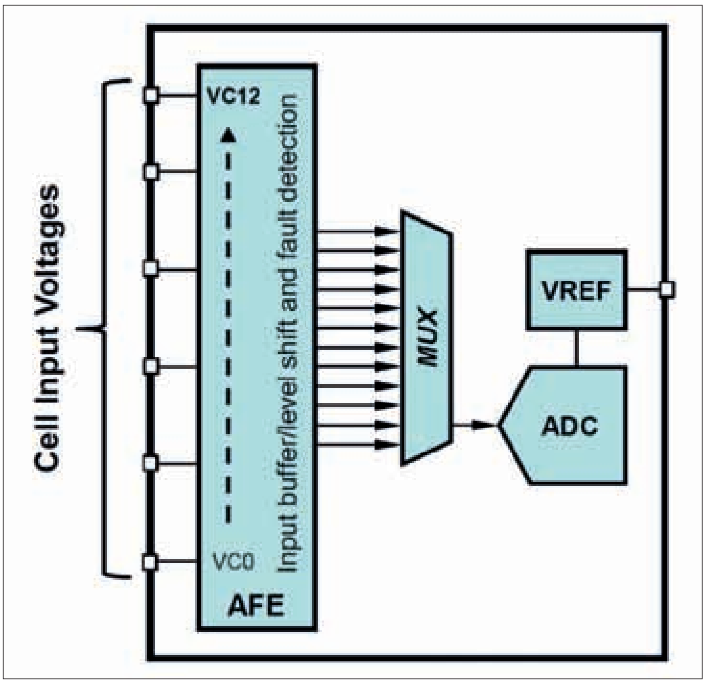
Optimizing Battery Accuracy for EVs and HEVs

Automotive battery management system (BMS) technology has advanced considerably over the last decade. Today, several multi-cell balancing (MCB) IC features play a key role in meeting the stringent safety, reliability and performance requirements of battery systems in electric vehicles (EVs), plug-in hybrid electric vehicles (PHEVs), and hybrid electric vehicles (HEVs). IC manufacturers such as Intersil are now integrating key features such as internal cell balancing and current measurement.

One of the critical functions of a BMS IC is the accurate measurement of individual cell voltages, which has a direct influence on battery life and range over the vehicle's service life. Accuracy is particularly important for battery cell types that have a flat discharge curve, like lithium-iron phosphate cells, which benefits smaller packs due to their low internal impedance. These cell types needs to detect small changes in cell voltage as the battery discharges. Measuring small cell voltage changes requires a sophisticated combination of accurate and stable voltage reference, an analog front end (AFE), and a precision analog/digital converter (ADC). Detecting these changes has become critical for accurate state of charge (SOC) and state of health (SOH) calculations.

Key elements in a multi-cell balancing IC

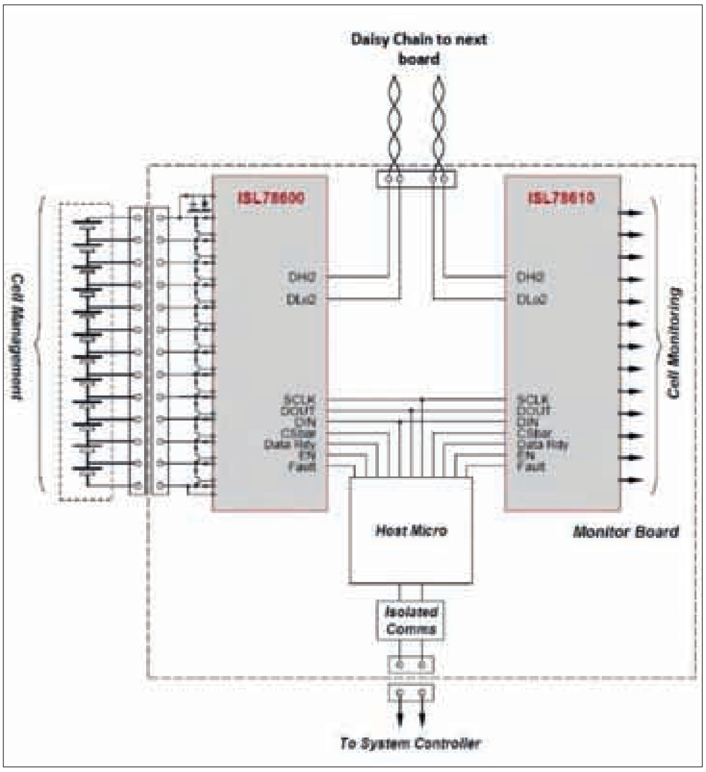
At the core of any MCB IC is a precision reference. The types of reference topologies employed can vary, although bandgaps tend to be the most



Simplified diagram of the ISL78600's three functional blocks and their interconnection

commonly used due to their optimal trade-off in accuracy versus die area. For example, the ISL78600 multi-cell Li-ion battery manager uses a precision bandgap reference which is well characterized, and has been optimized over many years of use.

Along with a precision reference, the ADC is another key functional block for measuring accuracy. Two of the most popular and commonly used types of ADCs are successive approximation register (SAR) and delta-sigma. Having the fastest sampling rate of the two technologies, the SAR offers high-speed voltage conversion and excellent noise immunity, but tends to require a larger die area. SAR ADCs also offer the best combination of data acquisition speed, accuracy, robustness and immunity to the effects of EMI. On the other hand, IC designers like delta-sigma ADCs because they typically require less die area, and are relatively easy to implement. However, they tend to be slower because they use a decimation filter, which reduces the sample rate and data acquisition speed. To overcome this issue,



The ISL78610 12-cell battery pack monitor serves as the redundant back-up device in an ASIL-D-compliant HEV/PHEV/EV system

two or more delta-sigma ADCs in an interleaved configuration can be used. Another consideration when implementing delta-sigma ADCs is their tendency to saturate when subjected to EMI, which causes the misreporting of cell voltages.

The individual cells' interface is managed by the AFE, which integrates input buffers, level shifters and fault detection circuitry. The AFE is key to handling hot plug transients when the cells are initially connected to the BMS. The ISL78600 is designed with a fully differential AFE that enables negative input voltages to be measured without affecting the adjacent cell measurements. This is advantageous in systems where bus bar interconnection is required. To improve robustness under transient conditions, an external low-pass filter is added to the cell voltage inputs. The input filtering requirements have been optimized for maximum EMI and hot plug immunity, without compromising speed or accuracy. By contrast, ICs that use a bipolar AFE rather than a charge coupled AFE can have their accuracy detrimentally affected by the component values selected for the input filter.

The combination of a stable and linear bandgap reference, SAR ADC and fully differential AFE gives a multi-cell Li-ion battery manager fast data acquisition capability combined with robustness and precision accuracy. Rather than relying simply on the measured accuracy values as it leaves the factory, the ISL78600's high accuracy is independently verified after mounting on a PCB.

Achieving ISO 26262 ASIL-D compliance

For hybrid and electric vehicles that require a redundant back-up battery management device, the ISL78610 battery pack monitor can be combined with the high accuracy ISL78600 multi-cell battery manager. This combination enables automobile manufacturers to achieve the higher ASIL-D rating.

Together, the ISL78610 and ISL78600 offer internal and external fault detection such as open wire, over- and under-voltage as well as temperature and cell balancing faults to mitigate battery pack failures. Multiple devices can be daisy-chained together to support systems with up to 168 cells using a proprietary communications system that provides transient and EMC/EMI immunity, which exceeds automaker requirements.

PCB layout and configuration considerations

Soldering induces stresses across the PCB, which "flexes" the MCB IC in the X and Y plane, and results in sub-atomic changes in the Silicon's properties. This effects the IC's behavior and, in particular, the reference circuit block. Since the reference is a critical part of the measurement circuitry, any variation in its characteristics has a direct effect on the accuracy of the ADC. This is a well-known and understood phenomenon in precision ICs, and designers make allowances for this by carefully placing sensitive circuitry in areas of the die less likely affected by soldering and other manufacturing stresses.

Alternatively, there are more costly reference design techniques available to designers, such as placing a separate reference circuit on its own die within the same IC package, or using a completely separate discrete reference IC. No matter which technique is used, the PCB design and manufacturing stage are both critical, so making use of standard precision part PCB layout and careful consideration for IC mounting and soldering profiles can help mitigate any issues.

MCB IC cell error vs. lifetime

For example, if designers follow the ISL78600's recommended PCB layout guidelines and soldering reflow profiles, the IC's board-level cell reading accuracy and long-term drift characteristics are logarithmic and predictable. This results in a typical cell reading error of only 1.2 mV over 10 years of service life.

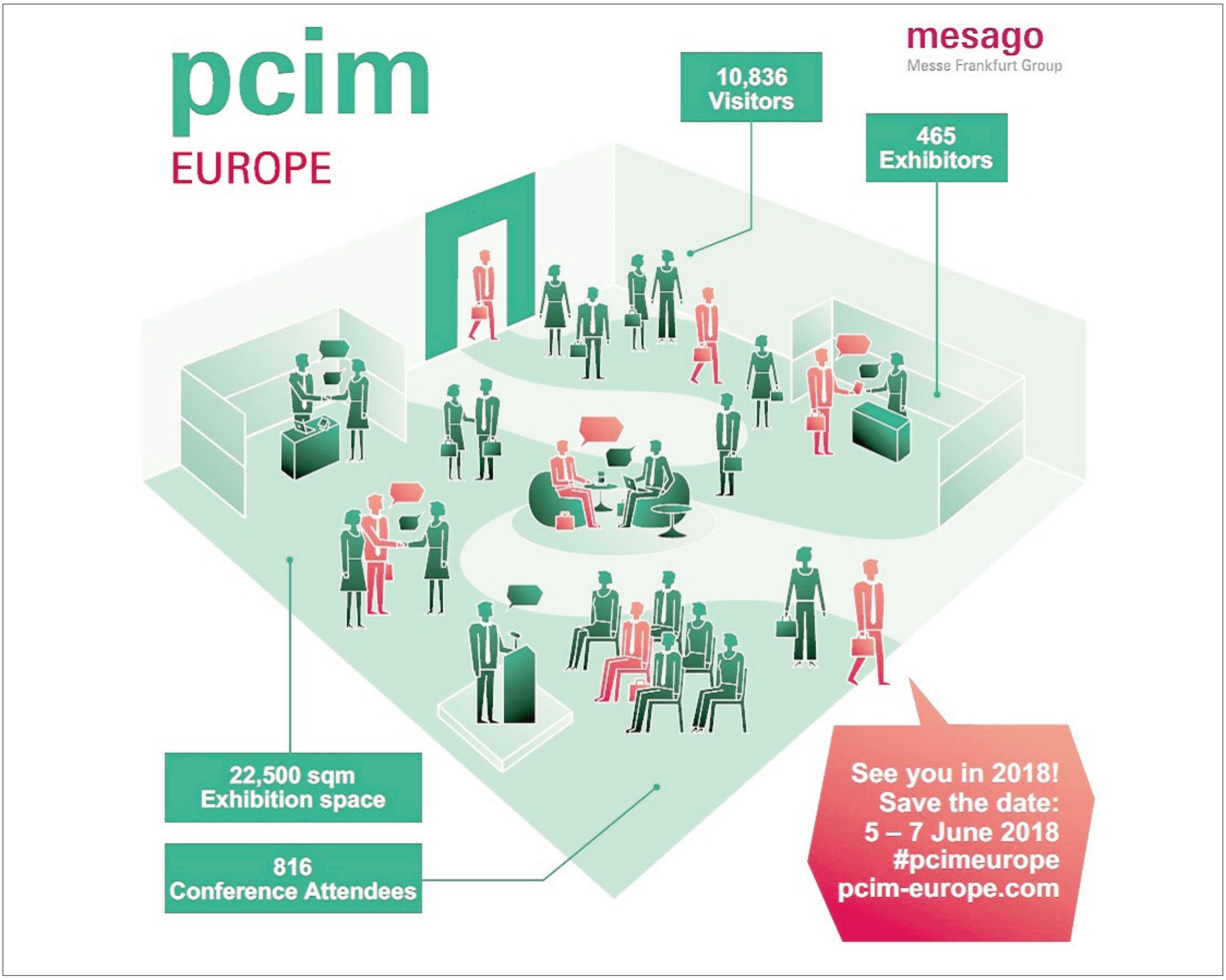
www.intersil.com

New Heights in Power Electronics

From May 16 – 18 around 460 exhibitors and 80 represented companies showcased new trends, developments and innovations from various fields of power electronics on an exhibition area of 22,500 square meters at Nuremberg fairgrounds. More than 10,000 exhibition visitors and over 800 participants of the international conference attended more than 300 lectures and poster presentations – making it the largest event ever. PCIM Europe 2018 will take place from 5 – 7 June 2018.

The power electronics market is influenced heavily by the power semiconductor market, which is estimated of around $17 billion in 2017 by market researcher Yole, in the year 2020 an increase up to $21 billion is expected. "Today is the starting point of replacing Silicon MOSFETs and IGBTs with SiC and GaN devices. The voltage range 600 – 900 V will become the battlefield SiC versus GaN. GaN devices rated at 600 V have passed the so-called hype cycle and are going now into applications", stated Yole's (**www.yole.fr**) Business Manager Power electronics, Pierric Guegen within a forum discussion on the fairgrounds.

Guest speakers in that forum were Peter Friedrichs, Senior SiC Director at Infineon Technologies (**www.infineon.com/sic**) and Marnix Tack, GaN Technology Leader at On Semiconductor (**www.onsemi.com**). "With SiC the way is open to unipolar concepts above 1200 V. SiC allows for higher switching frequencies even in the megahertz range, but also on lower switching frequencies can be better controlled and have lower switching losses due to the absence of tail current observed in IGBTs". SiC technology enables



PCIM 2017 enjoyed impressive results due to the increasing role of power electronics in industry and transportation

vertical structures within the devices, whereas in GaN on Silicon only lateral structures are possible – but with the advantage of better integration", stated Friedrichs. "Our new CoolSiC device, a 1200 V SiC trench MOSFET, we use the the intrinsic body diode along with the conduction channel as freewheeling diode, thus in new power modules no antiparalleled diode is necessary".

By the acquisition of Fairchild Semiconductors (**www.fairchildsemi.com**) in late 2016 On Semiconductor has access to SiC technology and has now designed an enhancement-mode 650 GaN device with on-resistances from 25 mΩ to 400 mΩ in PQFN 8x8 package, now sampling to qualified customers. This ends the cooperation with US-based GaN pioneer Transphorm (**www.transphormusa.com**), who have designed a cascoded (d-mode) GaN HEMT and On Semiconductor supplying the Si MOSFET for this cascode. "Over time pricing of GaN at component level will be lower than Silicon, we expect by 2022 a crossing with SJ MOSFETs. Thus GaN has the opportunity to become mainstream, but it will take up to ten or more years. Regarding applications travel adapters are a good starting point for GaN, automotive will follow sometimes", Tack said. "Regarding manufacturing technology MOCVD tools might open up the possibility of single wafer processing in a single chamber, decreasing cost and ramping up volume." MOCVD (metal organic chemical vapor deposition) is a technology that is used to deposit very thin layers of atoms onto a semiconductor wafer. It is the most significant manufacturing process for III-V compound semiconductors, especially for those based on GaN.

However, this does not necessarily mean doom for Silicon power MOSFETs. Looking back at the development of bipolar transistors and power MOSFETs in the past 20 years in different applications, there will still be a very solid market share reserved for Silicon power MOSFETs. Both SiC and GaN devices will penetrate the high frequency market, but the majority of the market will still use Silicon power MOSFETs, thanks to their proven reliability and good cost performance ratio, Yole predicted.

X-FAB Silicon Foundries (**www.xfab.com**) and Exagan (**www.exagan.com**), a start-up of GaN semiconductor technology, have demonstrated mass-production capability to manufacture high-voltage power devices on 200-mm GaN-on-silicon wafers using X-FAB's standard CMOS production facility in Dresden/Germany. This is the result of a joint development agreement launched in 2015, enabling cost/performance advantages that could not be achieved with smaller wafers.

Exagan, a spin-off of SOITEC in Grenoble and Toulouse in France and X-FAB have successfully resolved many of the challenges related to material stress, defectivity and process integration while using standard fabrication equipment and process recipes. Combined with the use of 200-mm wafers, this will significantly lower the cost of mass producing GaN-on-Silicon devices. By enabling greater power integration than Silicon ICs, Using substrates fabricated at Exagan's 200-mm epi-manufacturing facility in Grenoble, these epi wafers meet the physical and electrical specifications to produce Exagan's 650 V normally-on G-FET™ devices as well as the tight requirements for compatibility with CMOS manufacturing lines. Exagan's G-Stack™ technology enables GaN devices to be manufactured more cost effectively on 200-mm substrates by depositing a unique stack of GaN and strain-management layers that relieves the stress between GaN and Silicon layers. The resulting devices have been shown to exhibit high breakdown voltage, low vertical leakage and high-temperature operation. "This is a major milestone in our company's development as we accelerate product development and qualification," said Frédéric Dupont, president and CEO of Exagan. "It demonstrates the combined strengths of our epi material, X-FAB's wafer fab process and our device design capabilities. It also confirms the success of our vertically integrated fab-lite model, with expertise from materials to devices and applications."

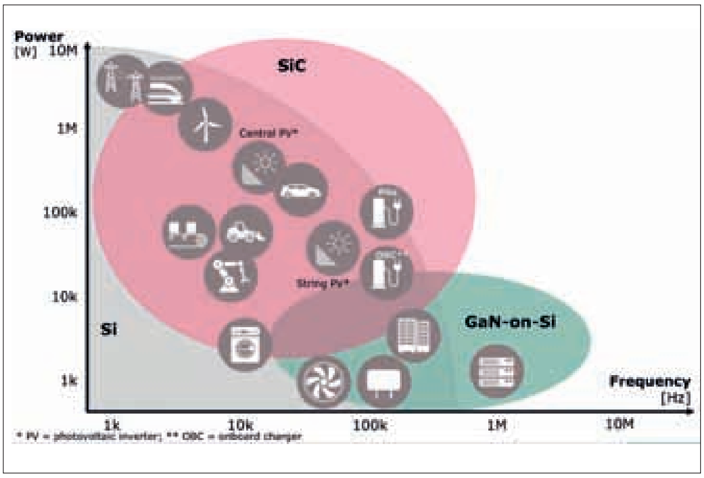
Asian partners are packaging the dies. "A PFC use case test featuring 200 kHz switching frequency shows the performance of our devices, and we are ready for mass production," Dupont stated at PCIM.

News on the exhibition floor

Higher efficiency, increased power density, smaller footprints and reduced system costs: these are the main advantages of SiC power transistors. Infineon Technologies is starting volume production for the Easy 1B, its first full-SiC power module. At PCIM the company showcased additional module platforms and topologies for the 1200 V CoolSiC MOSFET family (**www.infineon.com/coolSiC**). Easy 1B with B6 (Six-Pack) topology: the module features an on-resistance of 45 mΩ. The body diode works as a low-loss freewheeling function. Easy 1B is suitable for drives, solar or welding applications. Easy 2B with Half-Bridge topology: this larger module offers an enhanced performance with an on-resistance of 8 mΩ per switch. The low-inductance concept is ideal for applications with more than 50 kW and fast switching operations including solar inverters, quick-charging systems or UPS. 62 mm with half bridge topology: an additional configuration featuring higher power with an on-resistance of 6 mΩ per switching function. This module platform offers the possibility of low-inductance connection of systems in the medium power range. Applications include medical technology or auxiliary power supplies in the railway sector.

The lead products, Easy 1B and two discrete devices in TO-247-3pin and -4pin, are gradually entering volume production during this year. The half bridge configuration for the Easy 1B is now available along with various driver modules and demo boards.

"Silicon carbide has reached a tipping point, taking cost-benefit analysis into account, it is ready for use in a variety of applications," said Dr. Peter Wawer,



SiC and GaN enable higher efficiency through faster switching with lower losses than Si (Source: Infineon Technologies AG)

Infineon's Division President Industrial Power Control. "High efficiency can be realized with Silicon-based 3-level or SiC-based 2-level topology – at higher component pricing for the latter but at lower system cost due to higher switching frequencies of 10 to 40 kilohertz and thus smaller inductors and filters in an inverter. Our new SiC power modules use the MOSFET's internal body diode instead of a separate SiC freewheeling diode". The market favors now SiC MOSFETs, thus Infineon will introduce 650 V as well as 1.7 and 3.3 kV devices soon. According to Wawer JFETs now are out of focus.

The new 1200 V SiC MOSFETs show dynamic losses which are an order of magnitude lower than 1200 V Si IGBTs. First products will support applications such as photovoltaic inverters, UPS and charging/storage systems. An extended robustness is due to the lower failure in time (FIT) rate and the short-circuit capability, which can be adapted to the respective application. Thanks to a threshold voltage of 4 V and the recommended switch-on threshold of +15 V, the transistors can be controlled like an IGBT and safely switched off in the event of a fault.

Infineon's new CIPOS Mini power module (**www.infineon.com/IPM**) combines a single switch boost PFC stage and a 3-phase inverter in one package. It is designed to control induction motors and permanent magnet synchronous motors with single phase PFC in variable speed drives. These are typically found in applications like air conditioning and low power motor drives of up to 2 kW corresponding to inverter current ratings of 4 A, 6 A, 10 A, and 15 A. Designers can choose between PFC switching frequency of 20 kHz or 40 kHz. The package is especially designed for power applications which need good thermal conduction and electrical isolation.

Also a new package technology TRENCHSTOP Advanced Isolation (**www.infineon.com/advanced-isolation**) is available for TRENCHSTOP and TRENCHSTOP Highspeed 3 IGBTs featuring better thermal performance and simpler manufacturing. The two versions replace both fully insulated packages (FullPAKs) as well as standard and high performance isolation foils. By removing the need for isolation materials and thermal grease, assembly time can be reduced by up to 35 %. The thermal resistance of the new package is 50 % lower than with a TO-247 FullPak and 35 % lower than a standard TO-247 with an isolation foil. These improvements translate into a better performance such as a 10 K lower operation temperature than a FullPak with similar IGBT. System efficiency can be increased by 0.2 % over standard TO-247 with isolation foil.

LEM (**www.lem.com**) expands its miniature, IC transducers range for AC and DC isolated current measurement up to 300 kHz with the introduction of the GO series. These new components offer full isolation, despite their small size, by integrating the primary conductor for nominal current measurements of 4 - 30 A with a measurement span of 2.5 times the nominal current . Products in the GO series are able to support high overload currents up to 200 A peak for 1 ms. The transducers are mounted directly onto a PCB as SO8 or SO16 SMD devices.

GO models are simple to use as they integrate low resistance primary conductors within a proprietary ASIC to allow DC measurement and consistent insulation performance, while still providing high creepage and clearance distances. Standard models provide an analogue voltage output with different sensitivity levels according to the models to achieve an output voltage of 800 mV @ IPN for 5V versions and 500 mV @ IPN for 3.3V versions. Ratiometric output is also an option though dedicated models. GO transducers are not simple Open Loop Hall effect ASIC-based transducers; the series has been designed with unique primary integrated conductors for gradient measurement, to provide an excellent immunity against the external fields found in power electronic applications.

These dedicated designs combine field proven techniques such as spinning, programmable internal temperature compensation (EEPROM), which ensure high-performance accuracy over the full range of temperature, from -40 to +125°C with a maximum deviation of 3.74 %. Absence of a magnetic circuit contributes to achieving this accuracy as that means that there is zero magnetic offset generated. The accuracy over temperature and response time have been greatly improved in comparison to the previous generation. The GO series achieves a short response time of 2 µs, which is very similar to the response time of a transducer with a magnetic circuit. The SO16 package, provides two different Over-Current Detection (OCD) warning levels as a standard on 2 dedicated pins; one very fast, and the other slower but more accurate.

Some applications, particularly for motor drives, have the same need for speed but are less demanding of the current range and isolation levels while having strong pressure on price and dimensions. An example of this need is for white-goods, window shutters and air-conditioning, GO is the solution as it is low cost, and very small. The GO series can easily compete against other traditional low cost current measurement solutions such as shunts, commonly used for cost reasons, but in additional to the usual benefits of a shunt, GO brings natural insulation.

Mersen (**www.mersen.com**), has teamed-up with AgileSwitch (**www.agileswitch.com**) and FTCAP (**www.ftcap.de**) to develop two high performance 3-phase SiC and IGBT power stack reference designs. The SiC reference demonstrator has been designed using Wolfspeed SiC modules with power density value of 16 kW/l for SiC 150 kVA heavy-duty Electric Vehicle (EV) inverter, exceeding US Department of Energy (DoE) 2020 roadmap. The IGBT reference demonstrator has been designed in the frame of Infineon Industrial Power Partner Network (IPPN), powered by IGBT5 with .XT technology from Infineon and targeted for Electrical Energy Storage (EES) applications. The Silicon IGBT5 .XT 500kVA demonstrator achieved 25 kW/l.

The Silicon reference design is operating at 8 kHz and delivers up to 750 kVA. The SiC reference design is built around a 3-phase, 700 VDC / 200 A water-cooled converter, powered by three Wolfspeed CAS300M12BM2 modules pushed up to 20 kHz switching using AgileSwitch's 62EM1 Gate Driver with patented Augmented Switching and advanced fault monitoring. For both designs, a custom DC-link capacitor bank (700 V/3,500 µF for IGBT and

Mersen's SiC reference design is built around a 3-phase, 700 VDC / 200 A water-cooled converter

1,000 V/760 µF for SiC) has been specifically developed by FTCAP to minimize the footprint and optimize the thermal transfer to the heat-sink underneath. High temperature, low inductance, AC and DC Mersen laminated busbars are designed to minimize skin-effect induced by ripple-current.

New generation of power modules, such as Infineon PrimePACK™ IGBT5 with .XT or SiC MOSFET are exhibiting enhanced power density in the same footprint. Whereas this added-value is definitely a plus for inverter or power stack designers who can therefore increase the overall system efficiency, it brings some new challenges on the cooling, busbar, gate driver and capacitor sides. Essentially these surrounding devices define the overall inverter dimensions and ultimately the final power density value.

Littelfuse/Chicago and Monolith Semiconductor/Austin (**www.littelfuse.com, www.monolithsemi.com**), a fabless supplier of SiC Schottky diodes and MOSFETs, have fabricated 1200V, 65 mΩ SiC MOSFETs from multiple lots with various process and design split that are fabricated on a 150 mm CMOS line at X-Fab/Texas. The devices have extremely low losses of <400 µJ with gate resistance of 4.8 Ω. At 0.2 Ω the turn-off dV/dt exceed 70V/ns, demonstrating extreme ruggedness. Short-circuit withstanding capability of these devices has been tested under different gate and drain voltage conditions. These characteristics can disrupt cost and reliability barriers of SiC MOSFETs and drive wide spread adoption. Working in an active Si foundry provides significant cost benefits. By using existing Silicon manufacturing infrastructure, the overhead costs can reduce to manufacture SiC devices, while maintaining high quality taking advantage of X-Fab's Silicon process controls and quality systems. The equipment, labor, and utility costs, are spread over the large volume of wafers (Silicon and SiC) processed at X-Fab. Monolith gains the cost advantage of high volume production even during initial low volume production of SiC devices. This approach is demonstrating the potential for significant cost savings over other competing SiC device manufacturing approaches, which use small or captured fabrication facilities.

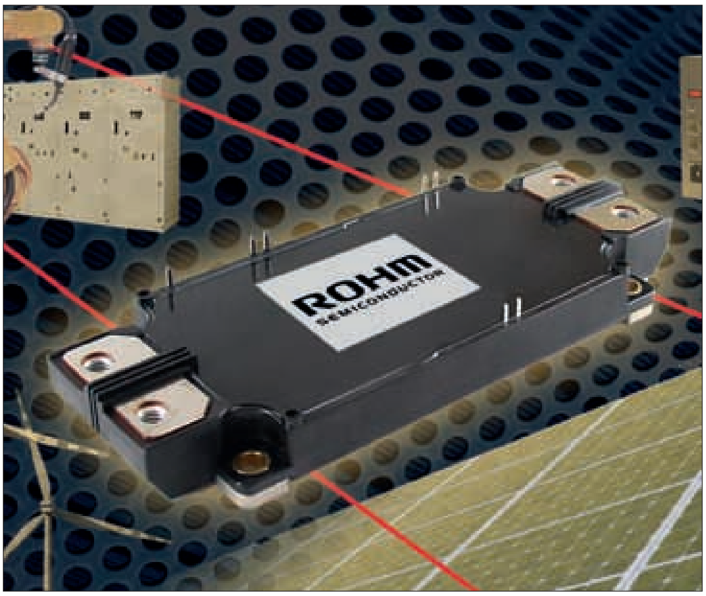
Mitsubishi Electric (**www.MitsubishiElectric.co.jp**) is according to market researcher IHS the leading manufacturer of power modules. At PCIM the company announced eight new X-Series HVIGBT modules in three (3.3 kV, 4.5 kV and 6.5 kV) classes for larger capacity and smaller sized inverters in traction motors, DC-power transmitters, large industrial machinery and other high-voltage, large-current equipment. The models will be released sequentially beginning in September including three 3.3 kV modules (one 1200 A and two 1800 A models), three 4.5 kV modules (900 A, 1350 A and 1500 A models) and two 6.5 kV modules (600 A and 900 A models).) The 7th generation CSTBT chip and RFC diode reduce power loss by about 20 %, package size by 33 %, and 150°C operating temperature enables a simplified cooling system. In addition, further line-up of SiC modules is planned in order.

The first 3.3-kV all-SiC power module with a performance suitable for a railcar traction system by using SiC MOSFETs and SiC SBD has been introduced at the conference. The new all-SiC power module has about 80 % lower switching loss than a conventional Si power module. In addition, the chips, module structure, and screening technology achieve sufficiently high reliability for actual use in a railcar inverter system. The main circuit system can consume about 30 % less power than the existing system. "Planar SiC technology is more robust than trench, thus in future trench devices a BWT layer will be introduced for balancing the electric field", stated Gourab Majumdar, Senior Fellow of Mitsubishi Electric in Japan.

ROHM (**www.rohm.com/web/eu/full-sic-power-modules**) introduced 1200V 400A/600A rated full SiC power modules [BSM400D12P3G002/ BSM600D12P3G001] optimized for inverters and converters in solar power conditioners, UPS, and power supplies for industrial equipment. Achieving full SiC power modules equipped with SiC SBDs and MOSFETs makes it possible to reduce switching loss by 64 % (at a chip temp. of 150°C) vs IGBTs at the same current rating. Loss simulations conducted with PWM inverter drive resulted in a 30 % reduction at 5 kHz drive and a reduction in total loss of 55 % at 20 kHz PWM vs equivalently rated IGBT modules. In the case of 20 kHz operation the size of the heat sink can be reduced by 88 %. High frequency drive also supports the use of smaller passive peripheral components. Increasing the current rating of power modules also increases the surge voltage during switching, making it necessary to minimize inductance within the package. Optimizing the internal placement of the SiC device along with terminal configuration and pattern layout allows to reduce internal inductance by 23 % vs conventional products. ROHM's new G Type package suppresses surge voltage by 27 % at the same loss compared with standard packages, enabling the development of 400 A and 600 A modules. In addition, this new package decreases switching loss by 24 % under the same surge voltage drive conditions. Achieving a rated current of 600 A entails not only reducing internal inductance but heat generation as well. By improving the flatness of the base plate section that significantly contributes to the heat dissipation of the module, the thermal resistance between the base plate and the customer's heat sink can be decreased by 57 %. In addition to SiC modules, ROHM also offers a gate driver board that enables quick and easy evaluation.

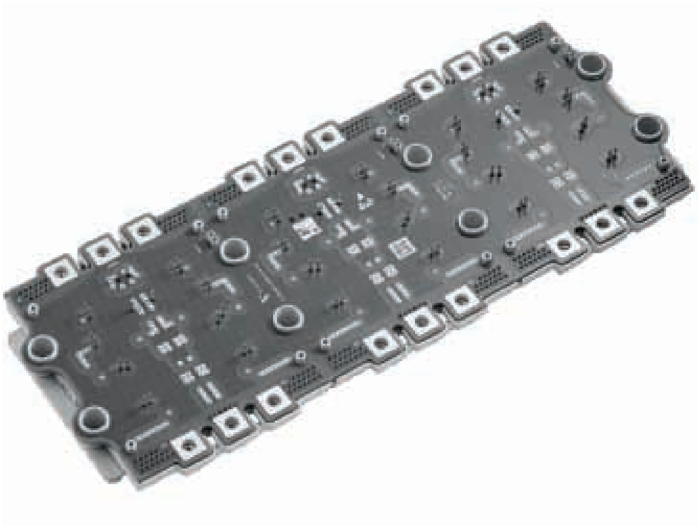
The first release of this series BM61S40RFV is a 3,75KV isolation, AEC-Q100 gate driver device specifically designed for SiC power MOSFETs. ROHM uses proprietary microfabrication processes to design on-chip coreless transformers for isolated gate drivers. The new device has an output current of 4 A, a built-in active miller clamp to prevent parasitic turn-on effects and integrates an under-voltage lock-out (UVLO) protection to prevent possible power switch damages due to thermal run away.

Based on an advanced field stop structure, ROHM's 3rd generation 650 V IGBTs offers a smaller carrier concentration gradient in the drift region leading to a better carrier distribution. Due to this fact, lower saturation voltage and faster switching becomes possible, overcoming the trade-off between saturation voltage and turn-off loss characteristics of conventional solutions. A trench gate structure reducing gate charge and capacitance and optimized cell structure, combined with a 15 % thinner wafer compared to the 2nd generation, decreases the total loss of the device. During conductive phase, there is less carrier concentration resulting in lower switching losses during turn-off. The new 650 V IGBT line-up consists of 30/50/80A types in RGTV Series and 30/40/50A in RGW series in two different packages - TO-247N and TO-3PFM.



ROHM showcased 1200V 400A/600A rated full SiC power modules

Vincotech (**www.vincotech.com**) launched a range of power modules, among others a remarkably powerful, efficient neutral-point clamped module, the VINcoNPC X12. Housed in a low-inductive package and featuring the latest IGBT M7 chips, this NPC module achieves high power density and 99 % efficiency. Rated for 2400 V / 1800 A and for up to 1 MW, the new VINcoNPC X12 is optimized for three-level topologies to simplify busbar design. Its design



Vincotech's new neutral-point clamped module, the VINcoNPC X12

and symmetrical layout serve to share current uniformly and distribute temperature evenly to extend component lifetime.

The new module is packaged in the low-inductive VINco X12 housing measuring 323 x 129.2 x 16 mm.

Wolfspeed (**www.wolfspeed.com**), a Cree Company a leader in silicon carbide (SiC) power products, has introduced among others a 650 V and a 900V, 10mΩ MOSFET rated for 196 A of continuous drain current at a case temperature of 25°C. This device enables the reduction of EV drive-train inverter losses by 78 % based on EPA combined city/highway mileage standards. This efficiency improvement offers designers new options in terms of range, battery usage, and vehicle design. "With the commercial release of the 900V 10mΩ device, electric vehicles can now reap the benefits of SiC in all aspects of their power conversion," said John Palmour, CTO of Wolfspeed. "With the continued expansion of our Gen3 MOSFET portfolio in new package options, our devices can now support significant efficiency improvements in onboard chargers, offboard chargers, and now EV drive trains." More details to be found in our feature 'Impact of Ultra-Low On-Resistance SiC MOSFETs On Electric Vehicle Drive-Train'.

Innovations from Talented Newcomers

Since ten years the PCIM awarded not only the best paper, but also young engineers for outstanding papers with a price money of Euro 1000.00, sponsored by ECPE, Infineon Technologies, and Mitsubishi Electric. This year's winner were Marco Denk from University Bayreuth in Germany, Frank Stubenrauch from Technical University Munich in Germany, and Tomoyuki Myoshi from Hitachi in Japan. The following gives an insight in their work.

Accurate Measurement of Junction Temperature and Inverter Output Current

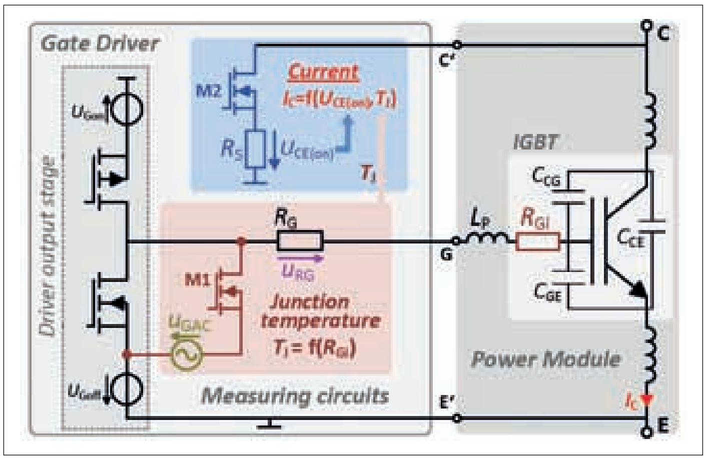
The first awardee presented a new gate driver that consists of two measuring circuits to determine the junction temperature and the output current of an IGBT or MOSFET power module during inverter operation.

To achieve this, a temperature and a current sensitive electrical parameter of the power semiconductor is measured simultaneously. This combined measurement is very useful in view of accuracy, because most promising current sensitive parameters are also temperature sensitive. For accurate current measurement the gate driver uses the on-state collector-emitter voltage $U_{CE(on)}$ and compensates the impact of the junction temperature by means of the on-chip internal gate resistor R_{Gi}. This paper focused on the accuracy of this new approach and presented two innovative measuring circuits to determine the internal gate resistor and the on-state collector-emitter voltage with high robustness and technical feasibility. Special attention is paid on the calibration and the implementation of the measuring concepts within a gate driver prototype. The sensor properties are examined in double-pulse tests and during the real inverter operation. With an overall error of 1-5 % the new gate driver represents a perfect solution to address diagnostic and functional safety issues, but also lower-performance control tasks, with minimum costs. For MOSFETs (Si and SiC) the concept is even more promising.

The internal gate resistor R_{gi} and the collector-emitter voltage drop $U_{CE(on)}$ has been indentified as the most promising parameter to realize a combined and accurate measurement of the junction temperature T_J and the collector current I_C on driver level. For real-time T_J-measurement the temperature of RGi is measured by means of a small identification signal that is modulated onto the gate voltage. To determine I_C the UCE(on) is decoupled and corrected by the R_{Gi}-measured junction temperature.

The new gate driver consists of a conventional output stage which has been extended by two simple measuring circuits to determine the temperature of the on-chip internal gate resistor and to decouple the on-state collector-emitter voltage. Both measurements do not affect the switching operation of the

Young Engineer Awardees Marco Denk, University of Bayreuth (left), Franz Stubenrauch, Technical University Munich, and Tomoyuki Miyoshi, Hitachi Source: Mesago/Thomas Geiger



New gate driver with integrated measuring circuits for combined real-time measurement of T_J and I_C

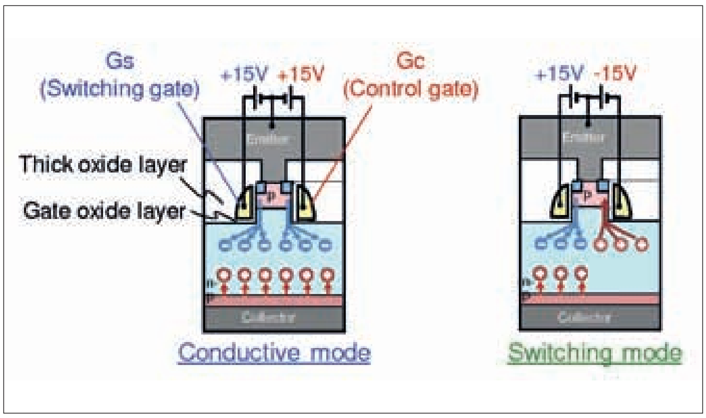
converter. Moreover, to calculate the junction temperature and the collector current on driver level the sensor system consists of two simple calibration functions CF1: $T_J = f_{(R\ Gi)}$ and CF2: $I_C = f_{(UCE(on)}, T_J)$. Thus, the gate driver offers data that can be processed immediately at higher system levels.

Dual side-gate High-conductivity IGBT Reduce Losses

For more than 37 years, insulated gate bipolar transistors (IGBTs) have been improved in terms of reduced power dissipation with lower conductive and switching losses by various technologies such as a scaling rule for IGBT and high-conductivity IGBT (HiGT) concept. However further improvement has been reaching a limitation.

A novel Dual side-gate HiGT (High-conductivity IGBT) with an extremely small feedback capacitance (C_{res}) and a function of controllable conductivity modulation was proposed by the second awardee. Dynamic control of stored carrier concentration right before switching by tandem drive of the dual gate makes it possible to further reduce switching loss with conventional single gate IGBTs. Compared with the single gate drive on conventional side-gate HiGT, the dual side-gate HiGT further reduces loss during turn-off and turn-on by 31 % and 12 %, respectively. As a result, an inverter system with dual side-gate HiGTs can reduce power dissipation by a further 15 % and break through the performance limit imposed by conventional IGBTs.

Driving two gates enables controllability of conductive modulation effectively. In the shown conductive mode, both side gates act to inject a large amount of electrons and thereby reduce the V_{CEsat}. Right before switching, one-side gate turns off while the other gate stays the on-state to reduce the amount of stored carriers, thereby enabling faster switching. In this work, a side gate structure was applied, because a side-wall gate surrounded by a thick oxide layer provides lower input capacitance (C_{ies}) and feedback capacitance (C_{res}) than the conventional trench gate structure. A low Cies structure could offer faster reactions to input carrier control signals. Furthermore, low C_{res}



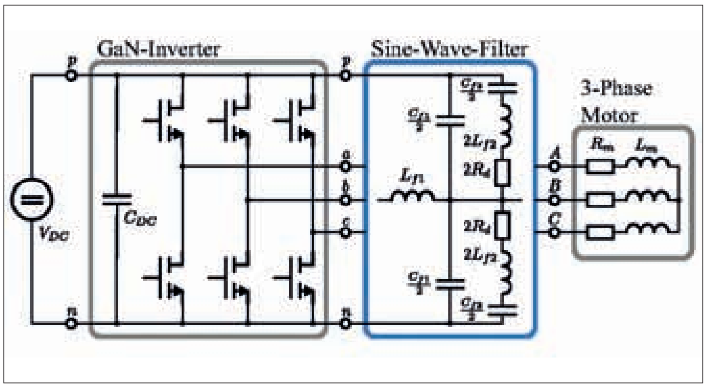
Concept and structure of proposed novel dual side-gate HiGT

characteristic leads to a shorter Miller period and lower turn-on loss (E_{on}). Therefore, a combination of a side-gate structure and a dual gate driving method creates a fast gate drive that can easily control a stored carrier and an effective solution for breaking through the limitation of conventional IGBTs' loss reduction.

The dual side-gate HiGT with an appropriate timing delay obtained 31 % lower E_{off} and 12 % lower E_{on} than the conventional single gate driving side gate HiGT, while maintaining low V_{CEsat}. This is the effect of stored carrier control method of dual side-gate HiGT. A novel module has 33 % higher power capacity than the conventional trench gate IGBT module.

200 kHz GaN Motor Inverter

Gallium Nitride (GaN) semiconductor devices are promised to be a good alternative to Silicon semiconductors in future motor inverters for variable frequency drives (VFDs). They combine low on state resistance and low switching losses with a high blocking voltage capability. Compared to actual inverters based on IGBTs the PWM frequency for efficient operation can be increased by a factor of 5 to 10, extending the PWM frequency range up to 500 kHz. This allows the use of motor filters with small component size. As a result, high motor efficiency, low torque ripple, high control bandwidth and nearly ideal sinusoidal output voltages are achieved. Therefore this



Schematic of the GaN motor inverter with sine wave filter and star connected 3-phase motor

inverters can be used for high speed spindle motors and dynamic servo drives.

The third awardee focused on the design of a hybrid sine wave filter consisting of an analog and a digital part. The filter is optimized to achieve low power loss and high current control bandwidth.

A 3-phase GaN motor inverter operating at 200 kHz 3-phase GaN motor inverter operating at 200 kHz PWM frequency at 400 V DC-link voltage. The GaN voltage source inverter (VSI) consists of three individual half bridges, each connected to the common DC-link voltage.. The half bridges are build by six GS66506T GaN-HEMTs, mounted on an aluminum cooler and controlled by Si8233 gate drivers with 4 A output current capability. The inverter is connected with the motor through a 3-phase sine wave filter.

The filter resonance is damped with a combination of an analog and a digital filter, resulting in zero phase-voltage overshoot at the output terminals. A high-current control bandwidth of the inverter is realized with a simple PI controller, located in series to the digital notch filter. The prototype confirms the theoretical considerations, which are sinusoidal phase voltages with very small ripple and a high closed loop current control bandwidth of 11 kHz.

Literature

"IGBT Gate Driver with Accurate Measurement of Junction Temperature and Inverter Output Current", PCIM Europe 2017 Proceedings, pages 220 – 227.
"Dual side-gate HiGT breaking through the limitation of IGBT loss reduction", PCIM Europe 2017 Proceedings, pages 315 – 322.
"Design and Performance of a 200 kHz GaN Motor Inverter with Sine Wave Filter", PCIM Europe 2017 Proceedings, pages 664 - 672

Air Cooled SiC Three Level Inverter Reaches Efficiency Levels Above 99 Percent

Power Electronics Europe has sponsored the Best Paper Award of PCIM Europe 2017. At Siemens a dual three-phase 3-level inverter (2 x 27 kW; input 600 VDC; output 2 x 400 VAC 45 Arms) has been realized with the latest generation of planar SiC-MOSFETs, a space saving embedding technology of power semiconductors, an optimized air cooling concept and a novel DC link configuration. The inverter has a high power density of 17,2 kW/l combined with an efficiency of 99,2 percent. With the new design the volume could be reduced by a factor of six in comparison to a standard high-performance Si-based converter. These features convinced the award committee to give the award (Euro 1000.00 and Invitation to PCIM Asia 2018), co-sponsored by Power Electronics Euope), to Alexander Hensler, Siemens AG, Nuremberg, Germany

Silicon Carbide (SiC) power devices have been significantly improved over the recent years. Especially the developments of 1200 V SiC MOSFETs are remarkable. These wide bandgap devices, combined with an optimized inverter design, enable new breakthroughs in power density and performance. Silicon-based devices with their bipolar behavior such as IGBTs have drawbacks due to the threshold voltage in the output characteristics (Figure 1) and much higher switching losses in comparison to SiC MOSFETs. For the assumption of 1 V voltage drop and typical switching losses of 50 %, maximum efficiency of about 99 % is reachable with 1200 V devices.

However, improvements of a drive application cannot be reached only by a replacement of Si devices with the new SiC MOSFETs. Especially, the fast switching of SiC devices requires a new approach of packaging and interconnection technology. A low inductive design is necessary to keep over-voltage and EMI low at high switching transients. Further aspects, such as inverter topology, cooling concept, gate drivers and power supplies have to be considered and optimized for SiC power devices. A new holistic approach for the inverter design can contribute remarkably to higher power density.

SiC inverter topology

Considering the electrical properties of SiC MOSFETs and a system benefit for the whole inverter, a dual T-type three level topology was chosen, as shown in Figure 2. Two 3-phase inverters enable

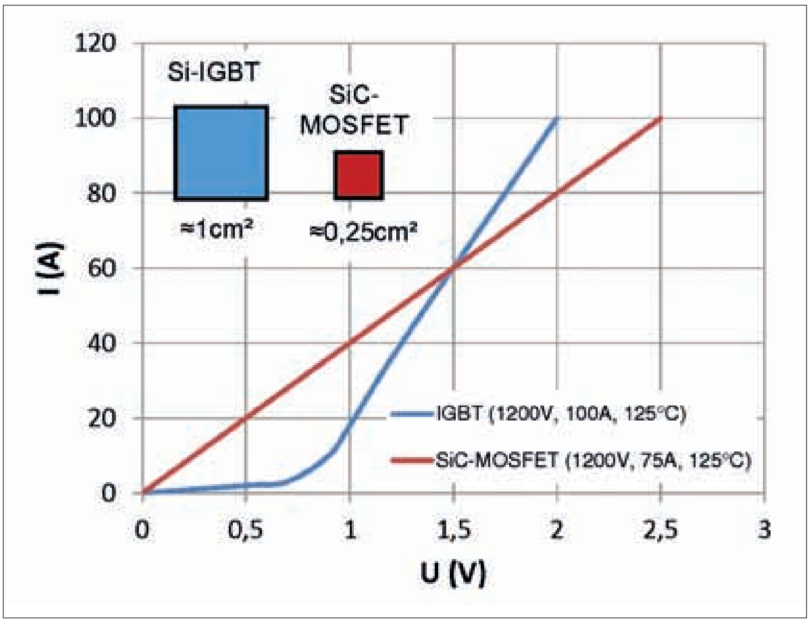


Figure 1: Output characteristics of IGBT and SiC MOSFET and comparison of chip area

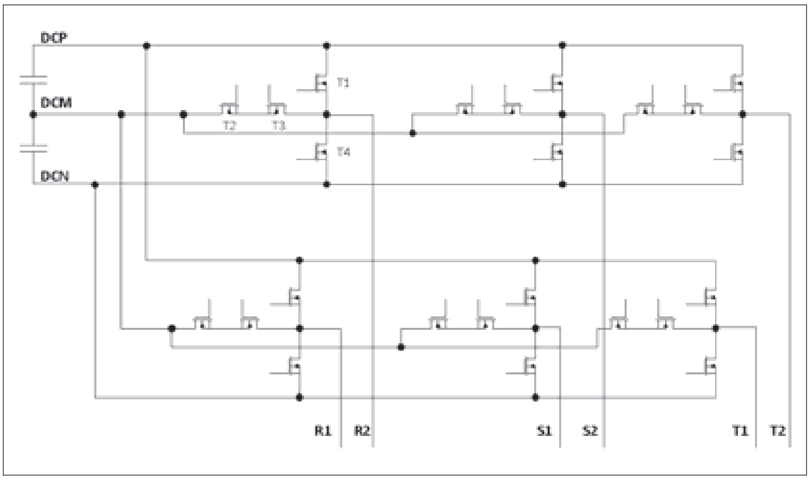


Figure 2: Dual T-type topology with SiC MOSFETs

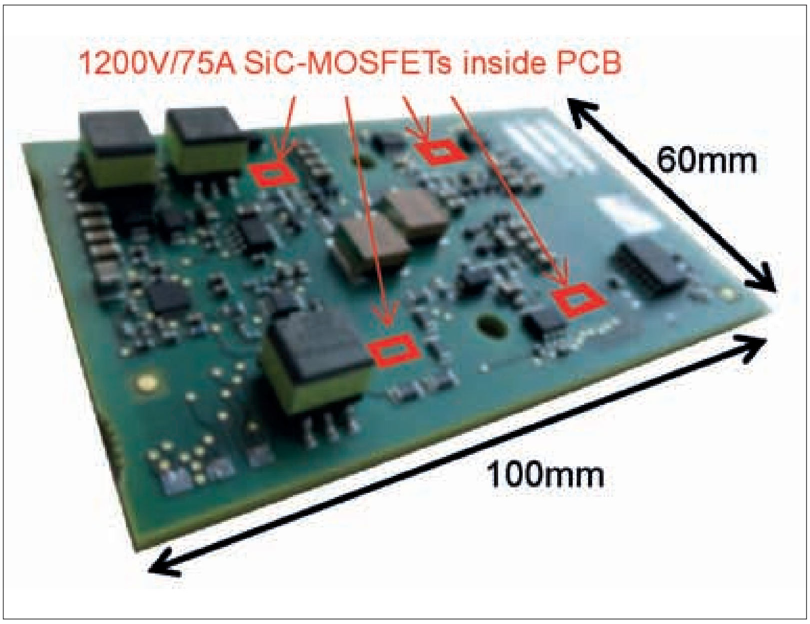


Figure 3: PCB-based half bridge with four embedded SiC MOSFETs and integrated functions

AC/AC operation. For DC/AC purposes, two inverters can be used for double-axis drive applications. Additionally, with a parallel connection of two inverters using external inductances, a higher output current is possible. Often, there are discussions whether a three level topology for SiC MOSFETs is reasonable. With much lower switching losses, the switching frequency can be increased and therefore improvements in comparison to a Si-based inverter are achievable.

Considering optional filtering, a three level inverter delivers additional improvements. Since the inverter design should cover the possibility of a drive solution with a filter for a pure sine output voltage, the T-type three level topology was chosen as the preferred solution.

The low switching losses of SiC MOSFETs combined with the advantages of a three level topology, a switching frequency of up to 100 kHz is reachable with acceptable switching losses. Under these conditions, an inverter solution towards ideal pure sinusoidal output voltage with a high power density is achievable, which corresponds with an evaluation of different topologies to Google's little box challenge.

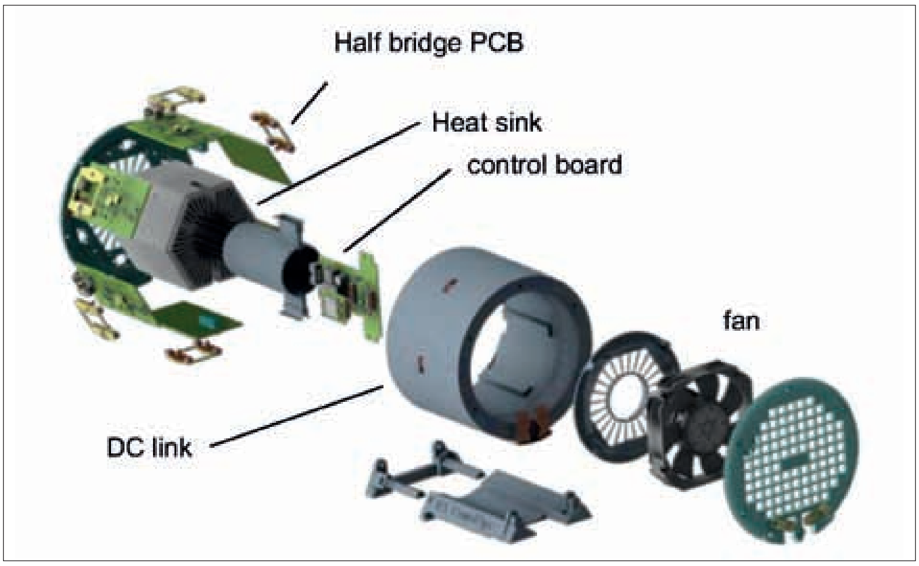
PCB-based half bridge

The whole converter consists of six half bridges. Each half-bridge (Figure 3) is realized with a multilayer printed circuit board (PCB). On the top side, there are three isolated auxiliary power supplies, gate drivers and measurement circuits for output current and output voltage. One half bridge has an additional measurement circuit for the two DC link voltages. For the current measurement, an isolated sensor, based on the magneto resistive principle, is utilized. Each PCB carries a part of the DC link capacitanc in form of a snubber capacitor (CeraLink™). Furthermore, on each PCB a temperature sensor is placed near to the hottest spot.

Inside the PCB, four SiC MOSFETs are embedded. All four power semiconductors of the half bridges are 1200V/75A devices. For the middle switch, between the midpoint of the DC link and the AC output of the inverter, two 650 V SiC MOSFETs would be sufficient, but were not implemented in favor for a simplification of the prototype design. There are no external parallel freewheeling diodes - the intrinsic body diode of the SiC MOSFET is used for inverter operation.

With a multilayer layer PCB a low inductive commutation circuit has been realized for the switching events between the SiC MOSFETs and the CeraLink capacitors. The main DC link capacitance is

Figure 4: **Exploded view of the prototype inverter**



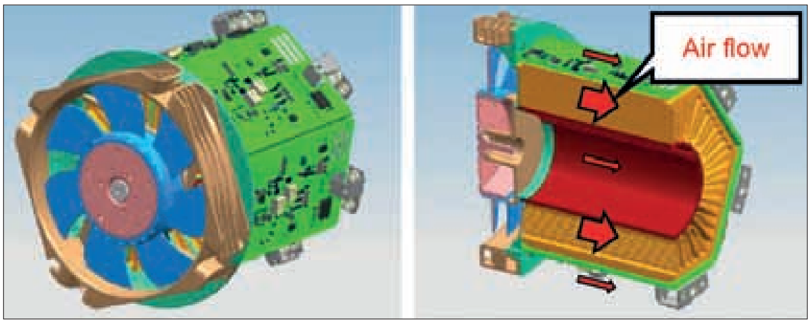


Figure 5: **Inverter cooling**

located externally and is not a part of the half bridge. On the bottom side of the PCB a thermal interface to the heat sink is provided. Also the interface to a control board is located on the bottom side.

Optimized cooling concept

The optimized cooling solution has the shape of a hexagon, the six half bridge PCBs are located with the thermal interface facing the flattened heat sink area. The fins are behind the active area of the fan. The inner volume of the heat sink is separated by a plastic tube and is used as a housing for the control board PCB, as shown in Figure 4. The main air flow streams directly through the heat sink fins, where the majority of the power losses have to be dissipated. A bypass air flow, shown with thinner red arrows in Figure 5, can additionally be used to cool the surfaces of the half bridge PCBs and the inner volume with the control electronics without additional cooling effort.

Another important evaluation step of the cooling is the thermal impedance between the SiC MOSFET and the heat sink. For the evaluation, the power device was embedded inside a PCB and mounted with a fixture on the heat sink. The temperature difference between the junction and the heat sink was measured during the cooling phase after the thermal steady condition was reached at known power losses, which was induced with a defined load current. The junction temperature was estimated by means of temperature sensitive voltage drop of the body diode at a constant measurement current and a known calibration function. The thermocouple for the heat sink temperature measurement was located 2 mm below the heat sink surface in the center of the chip.

DC link and overall inverter assembly

With the higher switching frequency of the SiC inverter, the DC link could be significantly reduced compared to Si-based devices. However, for industrial applications, there is a special demand for DC link capacitance. The inverter has to compensate short blackouts of power grids without failure. Therefore, the capacitance of the DC link is predominantly defined by the rated output power of the inverter. For the designed prototype, the addressed DC/AC output power of 2x27 kW at a rated DC voltage of 600 V requires 1,9 mF DC link capacitance.

The DC link is a series connection of two identical capacitors. With this configuration DCP, DCM and DCN potentials are provided for the three level topology shown in Figure 2. In the proposed inverter design the DC link is a ring-shaped assembly and is located around the hexagonal heat sink. The low profile design of the half bridge PCBs enables a very short and low inductive connection to the DC link capacitors. With this configuration, the whole DC link of the inverter is integrated into the housing. A further advantage is the thermal decoupling of the capacitor from the heat sink and the PCBs. The ring shaped capacitor can be realized by a simple winding process and is already established for automotive applications.

Conclusions

The proposed inverter design and the latest generation of 1200V SiC-MOSFETs lead to a very compact air cooled inverter for industrial applications. Additionally, an improved performance regarding the switching frequency was shown. Crucial for fast switching SiC devices is the low inductive design of the switching cell. The used embedding technology of the power devices into the PCB shows a possible solution to enable higher function integration combined with a low inductive design. The optimized cooling design keeps the PCB temperature relatively low - in an acceptable range for standard lead-free soldering capable FR4 materials and other used devices, placed on the PCB near to the power devices. With the DC link design inside the housing, a space-saving solution with high capacitance, suitable for industrial applications can be realized.

Literature

*A. Hensler, "Air Cooled SiC Three Level Inverter with High Power Density for Industrial Applications", PCIM Europe 2017 Proceedings, pages 2 04 – 21*1

CoolSiC Trench MOSFET Combining SiC Performance With Silicon Ruggedness

This article summarizes selected features of the new ColSiC™ MOSFET. The device combines low static and dynamic losses with high Si-IGBT like gate oxide reliability right fitting to typical industrial requirements. The temperature behavior, threshold voltage selection and Vgs_on makes the device easy to operate, in particular for operation in parallel. The switching behavior can be fully controlled by the gate resistor.
Dethard Peters, Thomas Basler, Bernd Zippelius, Thomas Aichinger, Wolfgang Bergner, Romain Esteve, Daniel Kueck, Ralf Siemieniec, Infineon Technologies AG

SiC MOSFETs based power switches offer significant system advantages in terms of power density, efficiency and cooling effort due to their much lower losses compared to Si-IGBT. It was shown that the system costs of solar applications as well as the running costs of UPS systems can be drastically reduced [1] despite the more expensive semiconductor component. Thus, the technology is ready to penetrate more and more applications in the coming years.

Reliability concerns solved

While the electrical performance of the commercial available SiC devices is already outstanding, there are still concerns about the SiC MOSFET reliability [2]. Currently most of the parts on the market are based on a planar DMOS like design. In order to mitigate the very low conductivity of the planar channel the devices are operated for full turn on at high gate oxide fields (using comparably thin gate oxides). Thus, special care needs to be taken particular about the potential high field failure rate as a consequence of the quite high permanent on state gate oxide stress fields of above 4 MV/cm [3]. The dilemma between performance and robustness can be overcome with the trench concept introduced by Infineon.

The CoolSiC MOSFET uses a trench structure showing commonly significantly higher channel conductivities due to less defects compared to the planar channel on the so called Si face of 4H-SiC. An investigation of different orientations of the trench sidewalls resulted in slightly different threshold voltages as well as significantly different channel mobility as shown in [4]. In Infineon's device the most favorable orientation with respect to the highest possible channel conductivity was chosen for the MOS channel.

Figure 1 shows a sketch of the CoolSiC MOSFET cell. Following the considerations presented before, the doped regions adjoining the trench are asymmetric. The left hand side of the trench sidewall contains the MOS channel which is aligned to the so called a-plane of 4H SiC. A large portion of the bottom of the trench is embedded into a p-type region which extends below the bottom of the trench which also acts a p-type emitter of the incorporated freewheeling body-diode.

CoolSiC MOSFET structure

This MOSFET structure inherently exhibits a favorable capacitance ratio. The miller capacitance CGD is small while CGS is comparably large. This allows for a well-controlled switching with very low dynamic losses [5]. In particular this feature is essential to suppress undesirable parasitic turn-on.

A decisive criterion to ensure gate oxide reliability of SiC MOSFETs is the limitation of the gate oxide field in order to guarantee a sufficient lifetime and FIT rate. For SiC trench MOS structures in blocking state additional care has to be taken since the electric field in the trench corners is enhanced due to the trench shape. With respect to this specific cell configuration the field peak is found in the left trench corners. This local maximum of the electric field determines the lifetime of the gate oxide in blocking state. Figure 2 presents a 2D simulation result for the electric field under worst case conditions, i.e. at maximum drain source voltage of V_{DSS} = 1200 V and a minimum gate voltage of V_{GS} = -10 V. The simulation indicates that the electric field in the gate oxide can be limited to a value sufficiently low not to conflict with gate oxide lifetime requirements.

The typical on-resistance for the single chip device is 45 mΩ at V_{GS}=+15 V, I_D=20 A and T=25°C. The threshold voltage is

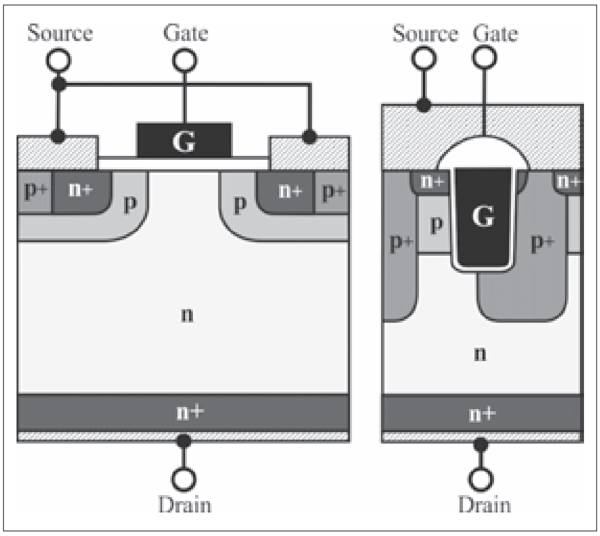


Figure 1: Sketch of a commonly known planar-gate MOSFET (left) and the CoolSiC™ Trench MOSFET cell

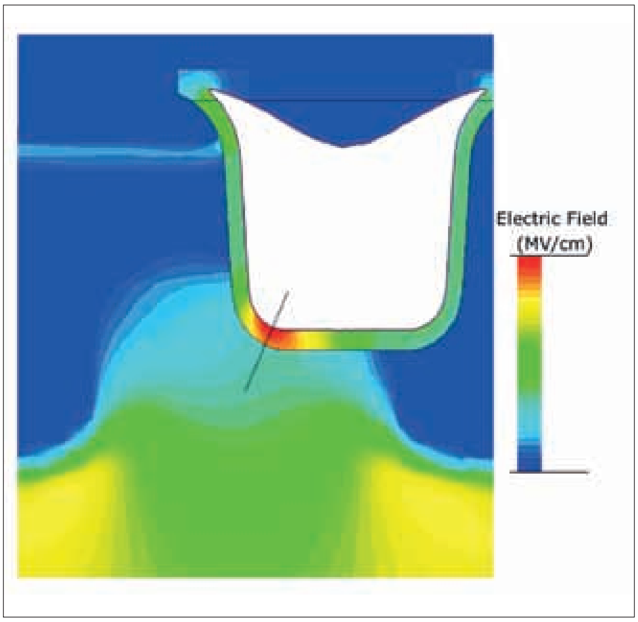


Figure 2: Simulation of the electric field in blocking state: The dotted line indicates the most critical area with respect to the gate oxide field

with typ. 4.5V significantly higher than for planar SiC MOSFETs. Thus, the part can be operated liked common IGBT's. The temperature dependency of the on-resistance and threshold voltage is plotted in Figure 3 within the specified temperature range between -40°C and 175°C. The on-resistance has its minimum at room temperature and increases from R_{DSon}=45 mΩ to typically 72 mΩ at 175°C. This represents the physically expected resistance increase with temperature of a MOSFET with a low defect density in the channel region.

The characteristics of the 3rd quadrant are given in Figure 4. As pointed out before the MOSFET contains a body diode which can be used for hard commutation. Thus, it is not necessary to add an external and expensive additional SiC diode for freewheeling operation. The curves with a gate source voltage of V_{GS}=-5 V represent pure body diode operation without a partial bypass by the MOS channel. At zero gate voltage there is already some contribution of the channel to the current which lowers the source drain voltage VSD. However, very low VSD and linear characteristics are found as soon as the channel is turned-on by applying +15 V to the gate. Now the corresponding 3rd quadrant on-resistance falls down to 33 mΩ at 25°C and 57 mΩ at 175°C, respectively. These values are lower compared to the 1st quadrant since the JFET resistance is reduced due to a negative feedback effect on the pn-junction bias. In order to keep static losses in diode mode low, synchronous rectification with an appropriate interlock time is recommended.

An essential feature of the MOSFET is that the voltage slope for turn-on as well as for turn-off is fully controllable by the external gate resistor in order to cope with any dv/dt limitations required by the system. Figure 5 proofs that the voltage slopes dv/dt for turn-off and turn-on can be easily adjusted by the external gate resistor R_{gext}. The switching losses are almost invariant to temperature as long as the gate resistor is kept constant. This behavior is in contrast to that of an IGBT since minority carriers do not impact the device behavior in the MOSFETs.

The dynamic behavior is mainly governed by the capacitances of the MOS system or by the built-up space charge regions. Both are in first order not dependent on temperature. In half-bridge configuration the body diode is active and shows an increasing impact with larger load current as well as higher temperatures. Obviously this is an effect due to minority carriers injected by the forward biased pn-junction which generates a reverse recovery charge. However, the absolute values at the rated current of 20 A are still reasonable small compared to the situation known from bipolar silicon devices and thus, will have just a minor impact on the total loss balance.

One of the most serious concerns about commercial SiC MOSFET is the reliability of the gate oxide which is impacted by extrinsic defects. The root cause for extrinsic defects in the gate oxide of SiC MOS devices is dominated by the substrate material, the epitaxial process, and by defects of the remaining process chain [6]. Hence, the challenge with respect to the gate oxide reliability of SiC MOS devices is how to ensure a low enough failure rate including extrinsic defects for a desired life time under given operation conditions, e.g. < 1 FIT in 20 y for industrial applications.

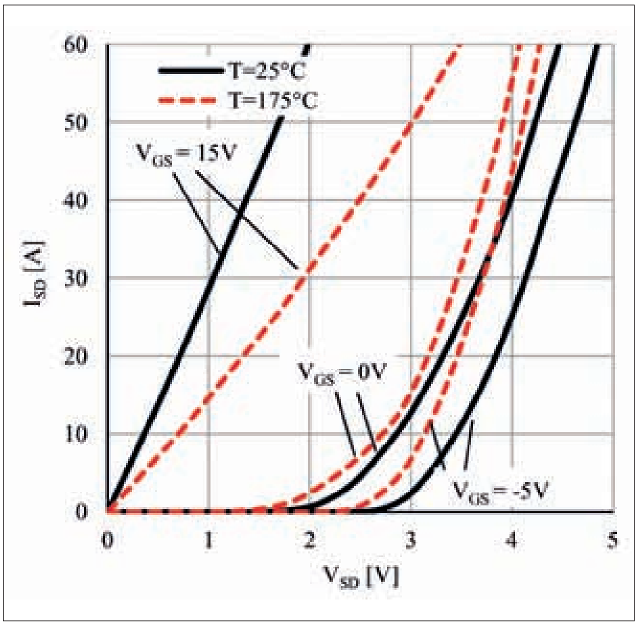


Figure 3: Typical 3rd quadrant characteristics at 25°C (black, solid) and at 175°C (red, dotted), V_{GS}=+15 V, 0 V and -5 V, resp.

Long-time gate stress tests

In contrast to the misleading reports of oxide reliability at high reverse bias which do not address the real challenge of SiC MOSFETs for practical applications long-time gate stress tests in on-state were performed with a large number of devices in order to determine the extrinsic gate oxide failure rates under real operating conditions. The investigation was done for 2 groups consisting of 1000 discrete devices. The tests were performed at 150°C under constant gate bias stress for 3 times 100 days each. The gate source voltage was increased by +5 V after each 100 days. The time stamp of each failure was monitored. Figure 6 shows the sum of fails after each 100 day sequence. In case of group G1 (green bars in Figure 6), the test started at a gate source voltage of +25 V with zero fails after 100 days. The test of group G1 ended at +35 V, which is +20 V

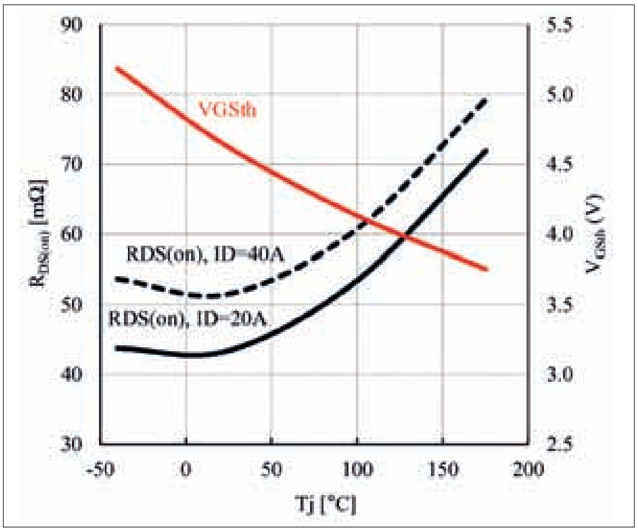


Figure 4: Typical temperature dependency of $R_{DS(on)}$ - black solid curve: V_{GS}=15 V, I_{DS} = 20 A, black dashed curve: V_{GS}=15 V, I_{DS}=40 A, red curve: V_{GSth} (at V_{GS}=V_{DS}, ID_S=10 mA)

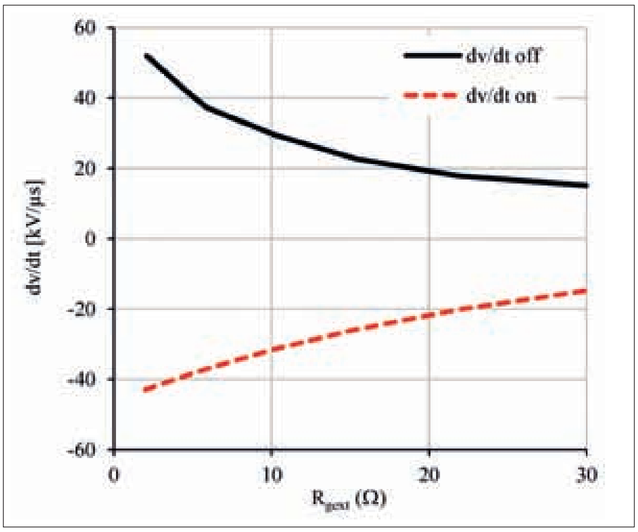


Figure 5: Maximum voltage slope dvDS/dt measured at turn-on (red) and turn-off (black) - switching conditions: 800 V, 20 A, 175°C, freewheeling diode IDH20G120C5, TO-247-3

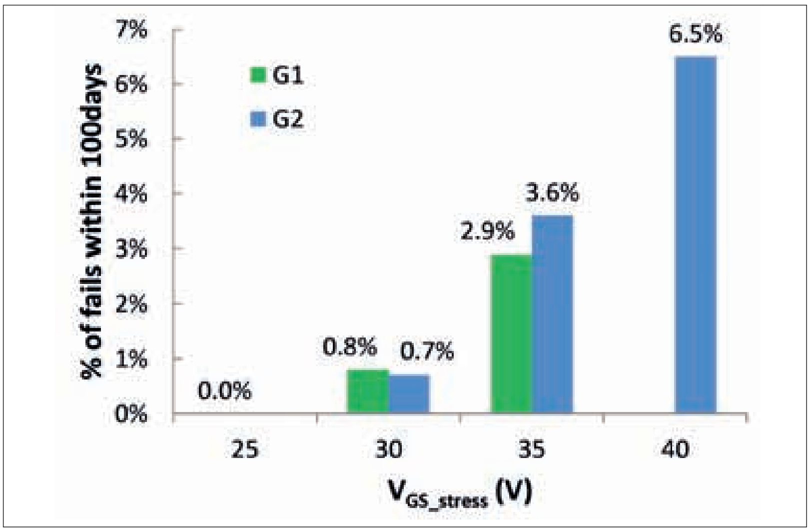


Figure 6: Failure rate after 300 days long term gate stress test. Two groups of 1000 SiC MOSFETs were tested at 150°C with constant gate stress which was increased by 5 V after 100 days

above the recommended use voltage of +15 V, with in total 2.9 % fails after 300 days. The 2nd group (blue bars in Figure 6) started at 30 V, continued at 35 V and ended at 40 V, with 6.5 % fails in total.

As could be demonstrated in [7], these failure statistics fit well to the linear E-Model. By extrapolating this result to a life time of 20 years of device operation, the model predicts a failure rate of 0.2 ppm. This experiment demonstrates an IGBT like reliability of the gate oxide with a failure rate under use conditions which is well below the typical industrial requirement specification of 1 FIT per die.

In addition, high temperature gate stress tests (HTGS) were performed. Both positive bias temperature stress (PBTI) as well as negative bias stress (NBTI) show well predictable power-law like threshold voltage shifts of the form $\Delta V_{GSth} \sim (time)^n$ which is similar to Silicon MOSFETs. Within 1000 h stress time at 150°C, the total threshold voltage shift reaches about +0.3 V for V_{GS}=+20 V and -0.1 V for V_{GS}=-10 V. Different to Silicon the BTI induced threshold voltage shift in SiC MOSFETs is superimposed by a fully recoverable on-off hysteresis [8]. This threshold voltage hysteresis is an intrinsic non-destructive feature of the SiC/SiO_2 interface and occurs most likely due to very fast charge trapping at interface defects.

From an application point of view, the more relevant permanent or slowly recoverable threshold voltage shift component is limited to some 100 mV for typical DC stress conditions (1000 h/+20 V/150°C). The remaining threshold voltage shift at the end of the BTI stress test is most likely due to charge trapping at defects within the gate oxide close to the SiC/SiO2 interface. A carrier trapped at such a site does not degrade the oxide integrity but needs more time to be released.

The authors would like to thank all Infineon colleagues who contributed to the results shown in this paper, in particular the teams in Villach, Munich, Warstein and Erlangen.

Literature

[1] S. Buschhorn, Proc. ECPE SiC&GaN UserForum, Apr. 20th, 2015, Warwick, UK

[2] Yole-Report "GaN and SiC Devices for Power Electronics Applications", 07/2015, www.yole.fr, p. 8

[3] M. Beier-Moebius, J. Lutz May 10th 2016, Proc. PCIM 2016, Nuremberg

[4] H. Yano, H. Nakao, T. Hatayama, Y. Uraoka and T. Fuyuki: Mater. Sci. Forum Vol. 556-557 (2007), pp. 807

[5] D. Heer, D. Domes, D. Peters, May 10th 2016, Proc. PCIM 2016, Nuremberg

[6] J. Senzaki et al., Mat. Sci. Forum Vols. 600-603 (2007) pp. 787-790

[7] D. Peters, T. Aichinger, T. Basler, W. Bergner, D. Kueck, R. Esteve, ECSCRM 2016, to be published in Mater. Sci. Forum in 2017

[8] G. Rescher, G. Pobegen, T. Aichinger, T. Grasser, Proc. of IEEE Int. Electron Devices Meeting IEDM'16, Dec. 2016.

The Big Five IoT Challenges

If industry predictions are accurate, we're on the cusp of an Internet of Things (IoT) explosion: forecasts suggest tens of billions of components will soon be using the IoT to transmit data or receive operating instructions. These connected 'things' could be anything from basic sensors to complex machines, such as aircraft or cars. Power management of these devices are crucial. **Andrea Dodini, European Marketing Manager, Keysight Technologies, UK**

Many IoT components will need to be relatively simple and able to operate reliably and autonomously for long periods. But there's also a need for more complex components, such as data aggregation points and gateways between networks of connected devices and the wider world. But regardless of what their products will be used for, IoT designers face five common challenges.

Integrating an increasing number and variety of components

First - mixed-signal integrated circuit design has come a long way, and we can now make devices that are smaller, cheaper, more energy-efficient and better-performing than their discrete predecessors. The flip-side is that designs are more complex, with radio frequency (RF), analogue and digital functions all needing to be designed and housed on the same substrate. This complexity is a challenge worth tackling. Early evidence shows there's definite demand for these integrated components in the IoT world, a good example being low-powered microcontrollers with built-in wireless communication capability and interfaces to connect actuators and sensors.

The need for long battery life

Second - long battery life is essential if you're to minimize maintenance costs, particular when your designs feature large numbers of sensors. Lots of designers look to achieve the required energy-efficiency through low duty cycles and by implementing sleep and idle modes whenever possible.

Things become more complex in high-performance devices, where processors, displays and communications interfaces all require varying amounts of power. To achieve energy-efficiency here, designers must understand how the components or subsystems interact, and the impact this has on every element's power usage.

How much current does the device require in each operating mode, and how long will it spend in each? Can you accurately measure currents ranging from nanoamps to tenths of amps? Overall, advances in battery technology, circuit design, communication strategy and the ability to harvest energy locally are extending the operational lifespans of remote and unattended IoT kit. To take advantage of these developments and make the right software and hardware decisions, designers need to understand how each area will impact on the life expectancy and thermal requirements of their products. This will enable them to understand how the device will perform in real-world conditions.

The need for high power and signal integrity

Third - for any IoT device to operate reliably, signal integrity (SI) and power integrity (PI) must be high. This is particularly important in low-voltage or high-clock-frequency circuits, which are much less tolerant of crosstalk. The four key SI challenges are around a single net, the couplings where multiple nets meet, power distribution networks' power and ground paths, and electromagnetic interference (EMI). Designers can address these by minimising power delivery network impedance, shortening the return path lengths, controlling impedances through interconnects, reducing coupling by ensuring sufficient space between circuit traces, and through good shielding and grounding.

PI looks at how well source power is converted and transmitted to where it will be used. In the low-power devices many IoT designers are creating, DC supply voltages must be delivered within tolerances of just 1 %. These incredibly tight bands mean data and clock signals could be impacted by any transients, ripple or noise on the supply rails. The challenge

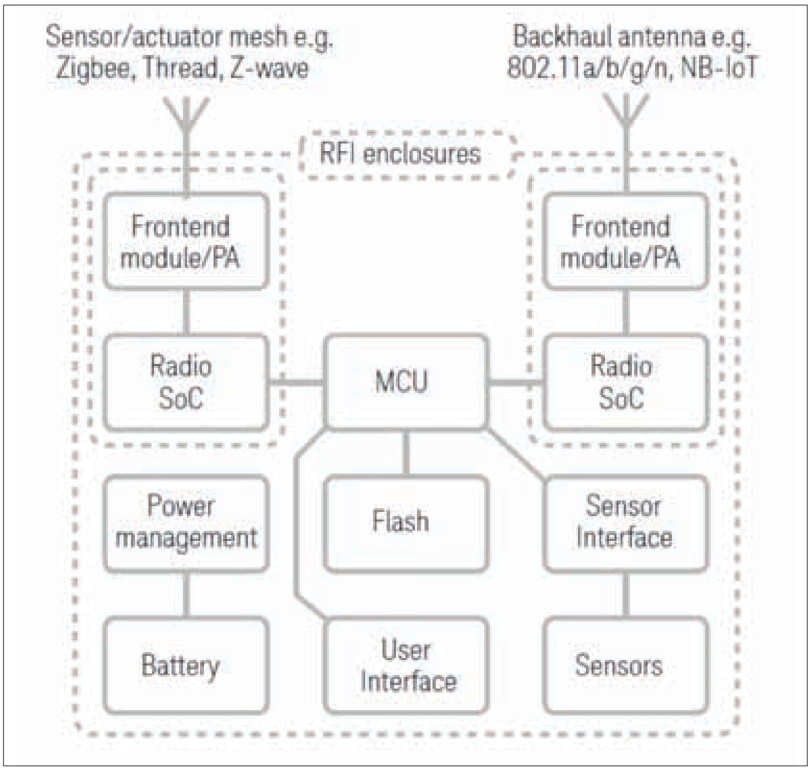


Figure 1: Many Internet of Things devices will be made up of numerous components, each of which will require varying amounts of power

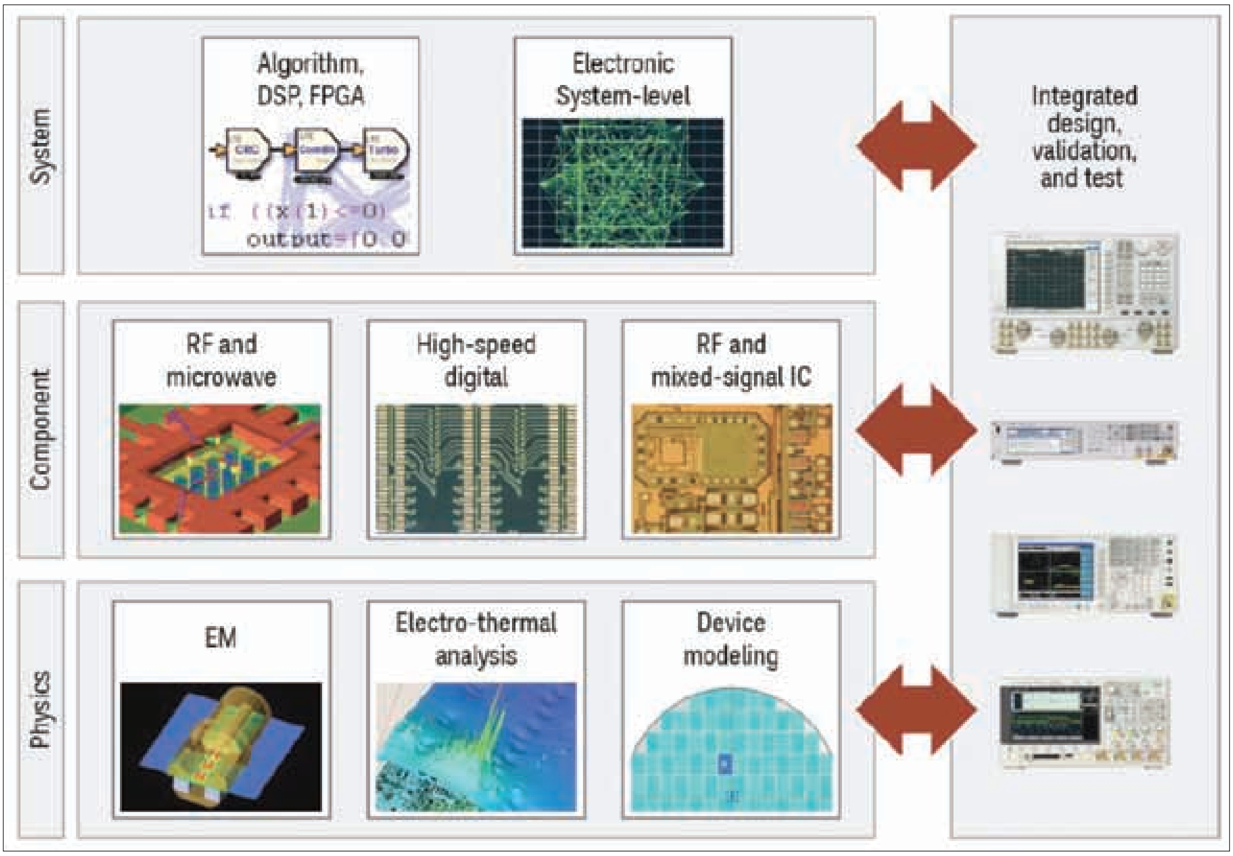


Figure 2: IoT designers can use Keysight's integrated tools to shape, validate and test their products

is to measure AC signals on these rails – as the signals continue to get faster and smaller.

Working with multiple communications standards

Forth- the huge range of use cases for IoT devices means lots of different wireless technologies and standards are emerging and being used. Where self-driving cars will need highly reliable, high-bandwidth connections, a sensor running off a small battery will likely use a short-range wireless connection with a low duty cycle. Other devices, such as smartphones, support multiple wireless standards (including Bluetooth, Wi-Fi, NFC and cellular).

Designing equipment that supports multiple standards makes measurement and testing increasingly complex, because each standard will have different test requirements. Designers need to ensure their components can work together effectively and adhere to more than one standard concurrently.

On top of the design challenges, testing compliance with multiple standards can be expensive if separate equipment is needed for each standard. This is why many are adopting flexible, multi-standard testing instruments that allow for the addition of new standards as these emerge.

Operating in increasingly crowded communications bands

Fifth- as the number of IoT devices expands, so communications resources are becoming more crowded, particularly the (unlicensed) ISM radio band. For

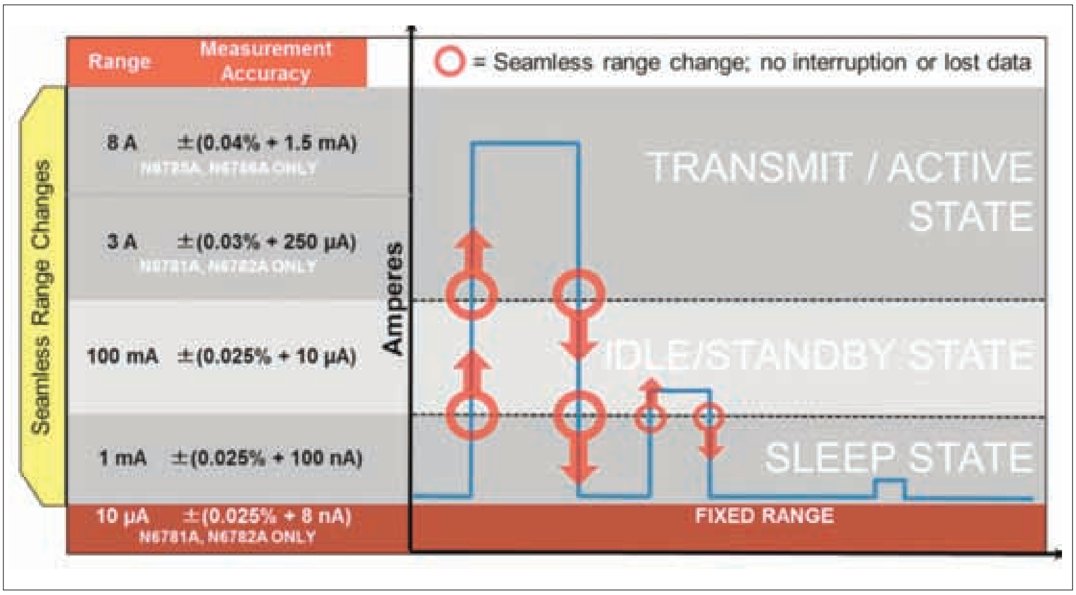


Figure 3: Many IoT devices draw different amounts of current at different times. SMUs enable designers to measure this in real time, thanks to seamless measurement ranging

Figure 4: **State-of-the-art testing hardware like the X-Series SA provides a consistent, full-lifecycle measurement framework for IoT devices**

designers, this means ensuring their products will work effectively in busy signal bands, without causing co-channel or adjacent-channel interference. This is essential if the products are to comply with network and regulatory requirements. Moreover, given that many IoT devices will be operating simultaneously and in close proximity to other equipment, they'll need to undergo radiated and conducted emissions and immunity testing. The tools used to test the devices must therefore also comply with the relevant standards.

Thus many Internet of Things devices will be made up of numerous components, each of which will require varying amounts of power (Figure 1).

Solving the challenges

Keysight EEsof is a suite of electronic design automation (EDA) tools that use design flows to enable IoT developers to simulate the operation of their products at the physical, component and system level (Figure 2).

System architects and algorithm developers can use SystemVue to test different ways of implementing their wireless communication systems' physical layer. This electronic system-level design tool comes with virtual measurement utilities for predicting how the system will perform.

Advanced Design System, or ADS, is for co-designing boards, packages and integrated circuits. Designers can use it to simulate products at circuit and 3D electromagnetic levels, even when the circuits comprise multiple technologies. ADS comes with 3D planar and 3D electromagnetic field solvers, electro-thermal analysis and a real-time optimization cockpit. Furthermore, it provides access to libraries for the latest wireless communication standards. ADS also supports signal integrity analysis, through its S-parameter and AC simulators. These calculate how much noise each component in the circuit will make and how this will impact the rest of the network.

SIPro, another element of ADS, is for electromagnetic characterization of high-speed links on complex circuit boards. Meanwhile, PIPro enables analysis of DC dynamic voltage (IR) drop, power-plane resonance and alternating current (AC) impedance.

Then there are electromagnetic simulation tools, encompassing FDTD, Method of Moments and FEM. These enable designers to analyse potential parasitic effects and coupling in a range of complex 3D structures.

A final tool to mention is GoldenGate RFIC Simulation Software, for mixed-signal radio frequency integrated circuit design. It offers a full design flow for IoT kit, linking design and analysis at component, subsystem and system levels.

To analyse battery current-drain, designers can use Keysight's source measurement units (SMUs), the N6781A or N6786A (Figure 3). Both offer seamless measurement ranging, to measure the dynamic current drain seen in many battery-powered devices. Furthermore, the units are able to mimic real batteries, while zero-burden voltmeters and ammeters enable run-down testing.

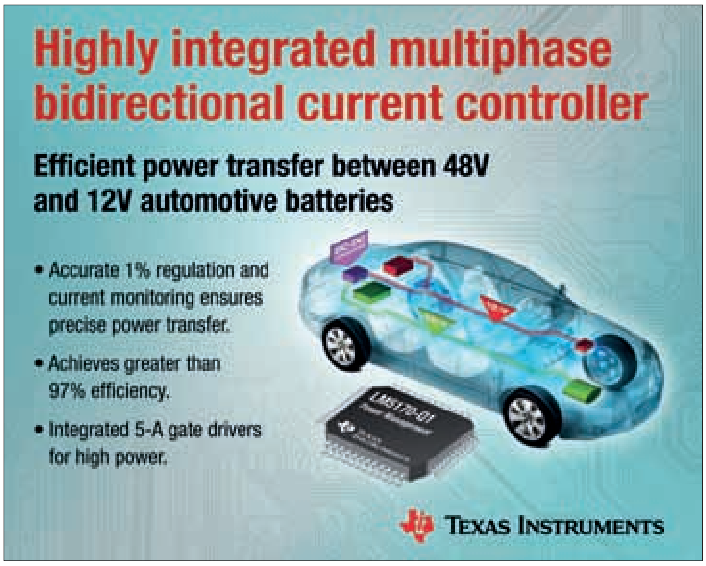
For signal and power integrity, you'll need tools to validate simulation results such as the ENA Option TDR (for interconnect test), Infiniium oscilloscopes (for transmitter test) and Bit Error Radio Test solutions (for receiver test).

To test wireless devices, Keysight has a range of one-box, benchtop and modular testers. These can be used throughout product development to provide a consistent measurement framework for easy comparison of results.

The testing platforms work with Keysight's Signal Studio, X-Series (Figure 4) and 89600 VSA software. Signal Studio enables designers to create bespoke, standards-compliant waveforms. X-Series provides the ease of one-button testing for different types of wireless. And 89600 VSA is a powerful digital modulation analysis tool, ideal for deeper troubleshooting.

Conclusion

Anyone designing for the IoT will face a common set of challenges. These include maximising energy-efficiency to prolong devices' operating lives, dealing with interference and ensuring compliance with a range of standards. The key to overcoming these hurdles more easily is to take advantage of integrated design, simulation and measurement tools.



Automotive Multiphase Bidirectional Current

TI's LM5170-Q1 controller provides the essential high voltage and precision elements of a dual-channel bidirectional converter for automotive 48-V and 12-V dual battery systems. It regulates the average current flowing between the high voltage and low voltage ports in the direction designated by the input signal. The current regulation level is programmed through analog or digital PWM inputs. Dual-channel differential current sense amplifiers and dedicated channel current monitors achieve typical current accuracy of 1 %. 5 A half-bridge gate drivers are capable of driving parallel MOSFET switches delivering 500 W or more per channel. The diode emulation mode of the synchronous rectifiers prevents negative currents but also enables discontinuous mode operation for improved efficiency with light loads. Versatile protection features include cycle-by-cycle current limiting, overvoltage protection at both HV and LV ports, MOSFET failure detection and overtemperature protection. An average current mode control scheme maintains constant loop gain allowing a single R-C network to compensate both buck and boost conversion. The oscillator is adjustable up to 500 kHz and can synchronize to an external clock. Multiphase parallel operation is achieved by connecting two LM5170-Q1 controllers for 3 or 4-phase operation, or by synchronizing multiple controllers to phase-shifted clocks for a higher number of phases. A low state on the UVLO pin disables the LM5170-Q1 in a low current shutdown mode.

www.ti.com/lm5170q1-pr

1200 V SiC Schottky Diode in SOT-227 Packages for Higher Power Applications

IXYS Corporation offers now the DCG85X1200NA and the DCG100X1200NA, both dual 1200 V rated SiC Schottky diodes in SOT-227 packages. The devices feature an average forward current of 43 A and 49 A, respectively, at 80°C case temperature. Both are rated at 1200 V blocking voltage in MiniBLOC™ SOT-227 package featuring 3 kV isolation to heat sink. IXYS also offers driver ICs such as the IXDD609SI, for high power SiC MOSFETs. Both diodes are electrically isolated from each other inside the package, allowing it to be free to connect to a common source or phase leg configuration. Additionally, the positive temperature coefficient of the forward voltage supports paralleling options for higher power applications. Typical applications, among others, are high efficient DC-DC converters, solar inverters, UPS systems and rapid-charger solutions.

www.ixys.com

LEM upgrades "ART" Rogowski current sensor to measure current of up to 10,000 A AC and beyond with Class Accuracy 0.5. The ART achieves IEC 61869 Class 0.5 accuracy without the need for additional components like resistors or potentiometers, which can drift over time. In addition, the ART benefits from "Perfect Loop" technology, a unique patented coil clasp that eliminates the inaccuracy caused by sensitivity to the position of the conductor inside the loop as well as providing an innovative, robust and fast "Twist and Click" closure. An internal shield is provided as standard to guard against external fields, improving accuracy and optimizing performance for small current measurements. The ART series provides the same ease of installation as existing split-core transformers, but with the benefits of being thinner and more flexible.

The ART also allows disconnection of the coil to be detected through the use of a security seal passed through a specially designed slot, making it really useful when used with a meter. It can be used in applications requiring a protection degree up to IP 67. This Class Accuracy 0.5 ART updated version completes the LEM City product solutions for the AC current measurement dedicated for future Smart Cities offering solutions for measuring electrical parameters in Smart Grids and Industry 4.0.

www.lem.com

Measuring High Dielectric Strength in Traction Batteries and Energy Storage

With its newly developed, shunt-based IVT-S measurement technology, Isabellenhütte offers specified functions in current measurement systems. The main focus is on achieving dielectric strength that is as high as possible in line with the intended application. High dielectric strength must be guaranteed in battery-powered vehicles, for example. These lithium-ion batteries generate high energy density at which higher voltages can be applied with smaller currents. This is why the sensor's dielectric strength also has to be correspondingly high. For fast-charging battery systems, this performance feature is extremely important. The IVT-S measurement system has a maximum dielectric strength of 1,000 V. Its functional range includes the measurement of current and voltage. A variety of components are used in the IVT-S. A 16-bit A/D converter guarantees the precise transformation of the voltage drop into digital signals. Data is transmitted through a CAN 2.0 interface. Through this module, the internally developed current counting firmware is provided with information on charge and discharge volumes. In addition Isabellenhütte provides a CAN description file in *dbc format that helps IVT-S users to swiftly integrate the application.

www.isabellenhuette.de

Broad Holding Current Surface Mount PPTCs

Littelfuse offers three new series of PolySwitch AEC-Q200 qualified resettable Polymeric Positive Temperature Coefficient (PPTC) devices. These surface mount devices are designed for robust over-current protection in extremely harsh automotive environments. Unlike fuses, resettable PPTCs do not require replacement after a fault event; they allow the circuit to return to the normal operating condition after the power has been removed and/or the over-current condition is eliminated. The largest of the new devices, the 2920-size ASMDC Series, has a lower profile compared to existing 2920 size ASMD series surface mount PPTCs, and no heavy metal terminals. It also offers the highest holding current and voltage rating of the three. The two smallest of these new devices, the 0603-size femtoASMD Series and the 0805-size picoASMD Series, are for applications in crowded automotive electronics boards. Typical applications for the ASMDC, femtoASMD, and picoASMD Series Resettable PPTCs include automotive infotainment, communications (GPS navigation), network (CAN Bus, LIN bus), body electronics (door locks, lumbar pumps), security (keyless entry, rearview camera), ADAS (advanced driver assistance system) and climate control systems.

www.littelfuse.com

DC/DC Converter Capable of DC Fan Motor Speed Control

ROHM offers now a buck DC/DC converter optimized for DC fan motor power supplies used in applications such as cold air circulation in refrigerators. Until now DC fan motor power supply blocks used in refrigerators and other equipment are primarily configured using discrete components, making it difficult to provide high accuracy control or carry out high frequency drive. As a result larger coils and output capacitors are required for the peripheral circuit, increasing mounting area considerably, which can be problematic. The BD9227F is the industry's first power supply IC capable of controlling the rotational speed of DC fan motors with high accuracy by linearly varying the output voltage based on the PWM duty signal generated by the MCU. In addition to more accurate control vs conventional discrete configurations, proprietary IC analog circuit design technology are used to achieve circuit optimization along with high frequency (1 MHz) drive. This supports the use of smaller peripheral components (i.e. coil, output capacitor), reducing footprint by 75 % while improving power conversion efficiency by 19 % (at 300 mA output), contributing to greater accuracy, increased miniaturization, and higher power conversion efficiency in DC fan motor applications.

www.rohm.com/web/eu/

Stepping Motor Driver IC Features Anti-Stall Feedback Architecture

Toshiba launched the TB67S289FTG, a stepping motor driver with a Toshiba-developed architecture that automatically detects and prevents stalling during operation. Mass production is scheduled to begin in the end of July 2017. Stable and highly precise control is a basic operating requirement, for motors used in printers, office appliances, banking terminals such as ATMs, cash dispensers, and home appliances. Recent demand has also emphasized more efficient motor drivers that use less power and generate less heat. Avoiding stalls in stepping motor operation is the highest priority for securing stability and precision in motor control, and is achieved by provision of additional current to assure an operating margin for the motor. Real-time monitoring of motor torque and current feedback, using additional sensors and highly advanced MCU control, are also required to improve efficiency and heat generation. A further way to improve efficiency and cut down heat generation is to adjust the built-in MOSFET's on-resistance and cut down power loss during operation. The TB67S289FTG is the first stepping motor driver to apply Toshiba's original anti-stall and efficiency improvement system, Active Gain Control (AGC), which enables the driver to monitor the motor and torque, and automatically optimizes motor control without additional MCU control. In operation, TB67S289FTG prevents motor stalls and automatically optimizes motor current, depending on torque needed. Compared with current solutions, TB67S289FTG cuts down the motor power by up to 80 % at best.

www.toshiba.semicon-storage.com

Accelerated Life Test Instruments

www.accelrf.com
Accel-RF Instruments Corporation
Tel: 001 858 278 2074

Arbitrary 4-Quadrant Power Sources

www.rohrer-muenchen.de
Rohrer GmbH
Tel.: +49 (0)89 8970120

Busbars

www.auxel.com
Auxel FTG
Tel: + 33 3 20 62 95 20

Capacitors

www.psl-group.uk.com
PSL Group UK Ltd.
Tel +44 (0) 1582 676800

Certification

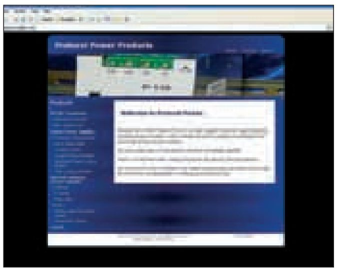
www.productapprovals.co.uk
Product Approvals Ltd
Tel: +44 (0)1588 620192

Connectors & Terminal Blocks

www.auxel.com
Auxel FTG
Tel: +44 (0)7714 699967

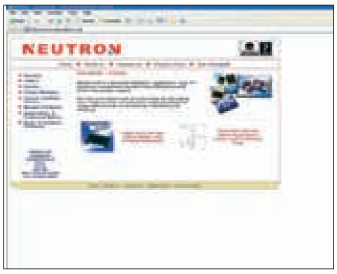
DC/DC Connverters

www.power.ti.com
Texas Instruments
Tel: +44 (0)1604 663399



www.protocol-power.com
Protocol Power Products
Tel: +44 (0)1582 477737

Diodes



www.neutronltd.co.uk
Neutron Ltd
Tel: +44 (0)1460 242200

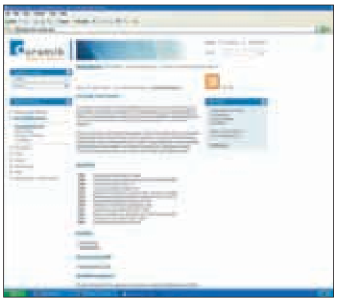
www.microsemi.com
Microsemi
Tel: 001 541 382 8028

www.voltagemultipliers.com
Voltage Multipliers, Inc.
Tel: 001 559 651 1402

Diodes

www.proton-electrotex.com/
Proton-Electrotex JSC/
Tel: +7 4862 440642;

Direct Bonded Copper (DPC Substrates)



www.curamik.co.uk
curamik® electronics GmbH
Tel: +49 9645 9222 0

Discrete Semiconductors

www.digikey.com/europe
Digi-Key
Tel: +31 (0)53 484 9584

www.microsemi.com
Microsemi
Tel: 001 541 382 8028

Drivers ICS

www.power.ti.com
Texas Instruments
Tel: +44 (0)1604 663399

EMC/EMI

www.dextermag.com
Dexter Magnetic Technologies, Inc.
Tel: 001 847 956 1140

Ferrites & Accessories

www.dextermag.com
Dexter Magnetic Technologies, Inc.
Tel: 001 847 956 1140

GTO/Triacs

www.mark5.com
Mark 5 Ltd
Tel: +44 (0)2392 618616

Hall Current Sensors

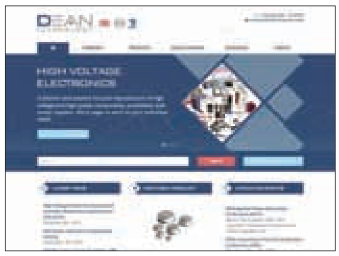
www.dgseals.com
dgseals.com
Tel: 001 972 931 8463

Harmonic Filters

www.murata-europe.com
Murata Electronics (UK) Ltd
Tel: +44 (0)1252 811666

High Voltage and High Power Electronics

Dean Technology, Inc.
www.deantechnology.com
+1 (972) 248-7691



IGBTs

www.microsemi.com
Microsemi Tel: 001 541 382 8028

www.power.ti.com
Texas Instruments
Tel: +44 (0)1604 663399

Line Simulation

www.hero-power.com
Rohrer GmbH
Tel.: +49 (0)89 8970120

Magnetic Materials/Products

www.dextermag.com
Dexter Magnetic Technologies, Inc.
Tel: 001 847 956 1140

www.rubadue.com
Rubadue Wire Co., Inc.
Tel. 001 970-351-6100

Mosfets

www.mark5.com
Mark 5 Ltd
Tel: +44 (0)2392 618616

www.microsemi.com
Microsemi
Tel: 001 541 382 8028

www.neutronltd.co.uk
Neutron Ltd
Tel: +44 (0)1460 242200

Optoelectronic Devices

www.digikey.com/europe
Digi-Key Tel: +31 (0)53 484 9584

www.power.ti.com
Texas Instruments
Tel: +44 (0)1604 663399

Packaging & Packaging Materials

www.curamik.co.uk
curamik® electronics GmbH
Tel: +49 9645 9222 0

Power Amplifiers

www.rohrer-muenchen.de
Rohrer GmbH
Tel: +49 (0)89 8970120

Power ICs

www.digikey.com/europe
Digi-Key Tel: +31 (0)53 484 9584

www.power.ti.com
Texas Instruments
Tel: +44 (0)1604 663399

Power Modules

www.psl-group.uk.com
PSL Group UK Ltd.
Tel +44 (0) 1582 676800

www.fujielectric-europe.com
Fuji Electric Europe GmbH
Tel: +49 (0)69-66902920

www.microsemi.com
Microsemi Tel: 001 541 382 8028

www.proton-electrotex.com/
Proton-Electrotex JSC/
Tel: +7 4862 440642;

Power Protection Products

www.power.ti.com
Texas Instruments
Tel: +44 (0)1604 663399

Power Semiconductors

www.psl-group.uk.com
PSL Group UK Ltd.
Tel +44 (0) 1582 676800

www.proton-electrotex.com/
Proton-Electrotex JSC/
Tel: +7 4862 440642;

Power Substrates

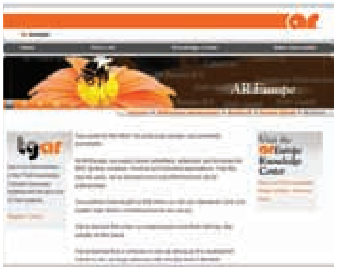
www.universal-science.com
Universal Science Ltd
Tel: +44 (0)1908 222211

Resistors & Potentiometers

www.isabellenhuette.de
Isabellenhütte Heusler GmbH KG
Tel: +49/(27 71) 9 34 2 82

RF & Microwave Test Equipment.

www.ar-europe.ie
AR Europe
Tel: 353-61-504300



Simulation Software

www.power.ti.com
Texas Instruments
Tel: +44 (0)1604 663399

www.universal-science.com
Universal Science Ltd
Tel: +44 (0)1908 222211

Smartpower Devices

www.irf.com
International Rectifier Co. (GB) Ltd
Tel: +44 (0)1737 227200

Switched Mode Power Supplies

www.citapower.com
Bias Power, LLC
Tel: 001 847.419.9118

www.power.ti.com
Texas Instruments
Tel: +44 (0)1604 663399

Thermal Management & Heatsinks

www.universal-science.com
Universal Science Ltd
Tel: +44 (0)1908 222211

Thermal Management & Heatsinks

www.psl-group.uk.com
PSL Group UK Ltd.
Tel +44 (0) 1582 676800

Thermal Management & Heatsinks

www.abl-heatsinks.co.uk
ABL Components Ltd
Tel: +44 (0) 121 789 8686

www.curamik.co.uk
curamik® electronics GmbH
Tel: +49 9645 9222 0

www.dau-at.com
Dau GmbH & Co KG
Tel: +43 3143 23510

www.power.ti.com
Texas Instruments
Tel: +44 (0)1604 663399

Thyristors

www.mark5.com
Mark 5 Ltd
Tel: +44 (0)2392 618616

www.proton-electrotex.com/
Proton-Electrotex JSC/
Tel: +7 4862 440642;

ADVERTISERS INDEX

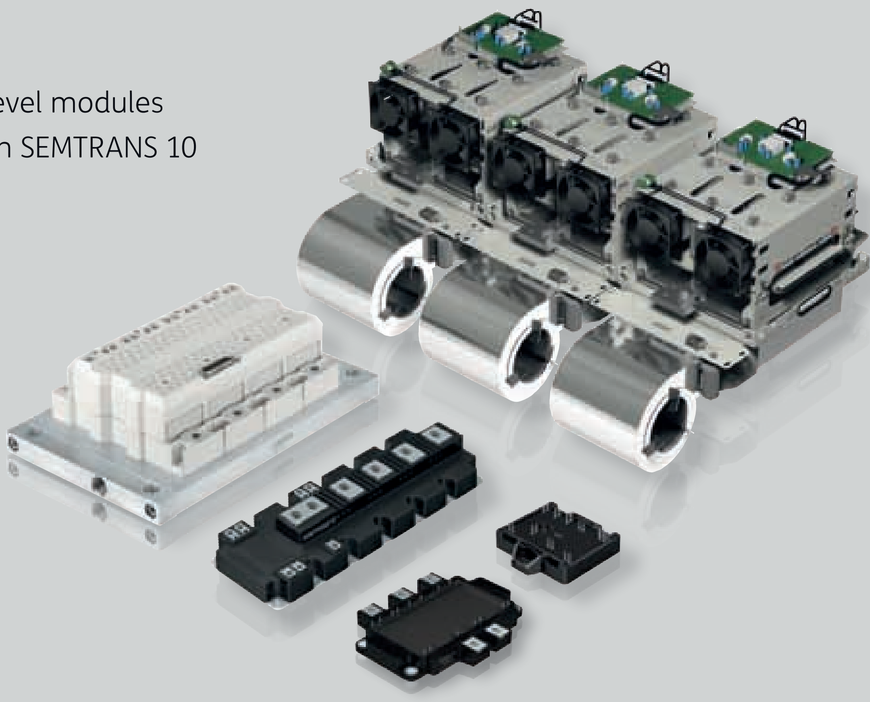
SEMIKRON
innovation + service

$1500V_{DC}$ in Solar? We cover all your needs.

Power Modules
- Broadest portfolio of 2-level and 3-level modules
- Up to 750kW without paralleling with SEMTRANS 10
- Plug & play drivers

IPMs
- 1700V SKiiP 4 product range

Power Electronic Stacks
- Ready-to-use power stacks and customized designs
- Including drivers with ASIC chipset
- IntelliOff function enabling $1500V_{DC}$ voltage



AC | DC

www.semikron.com/1500v-solar