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POWER GaN

GaN – Moving Quickly into Entirely New Markets

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COVER STORY

GaN – Moving Quickly into Entirely New Markets

Gallium Nitride (GaN) based power devices are rapidly being adopted due to their ability to operate at frequencies and switching speeds beyond the capability of Silicon power devices. With discrete GaN devices capable of switching at slew rates up to 70 V/ns, the system performance is greatly impacted by aspects outside the active power devices, such as high speed gate drivers and printed circuit board layout. The introduction of a new family of high performance enhancement mode eGaN FETs offers the potential to switch at higher frequencies and efficiency than possible with traditional Si MOSFET technology. Combined with an improved switching figure of merit and low parasitic packaging, the new devices also have optimized device pin-out to minimize parasitic PCB layout inductance to fully utilize the device's capability. Example buck converters operating at 10 MHz show experimental peak efficiencies of over 89 %. Although the results are impressive, there is still a significant loss component due to the current silicon gate driver. To fully utilize the capability of the new high frequency, reduced size eGaN FETs, a focused improvement in the gate driver structure is required, which in turn will allow a further increase in efficiency and switching frequency capability. In this article, the latest family of high frequency enhancement mode Gallium Nitride power transistors (eGaN FETs) is presented for use in multi megahertz buck converters. These devices were designed to address high-frequency hard-switching power applications at higher voltages. More details on page 28.

Cover supplied by Efficient Power Conversion (EPC)/USA.

A Further Push for SiC/GaN at PCIM

Silicon Carbide for power semiconductors is in research for decades, in the year 2001 the first product, a Schottky diode was launched. In 2006 the first SiC switches (JFETs) and in 2010 1200/1700 V SiC MOSFETs were announced. In the meantime new MOSFET generations namely by Cree and Rohm have been introduced, at PCIM 2014 Microsemi entered the SiC MOSFET arena. In addition to substantive performance gains, the SiC MOSFET has some other salient advantages. For example, SiC MOSFETs contain a rugged built-in body diode, which eliminates the need for an external anti-parallel Schottky diode in some applications.

According to market researcher IMS/IHS SiC diodes costs 5-7 x more than Silicon-based Schottky diodes, SiC JFETs 4-7 x more than Si MOSFETs, and SiC MOSFETs up to 15 times more than their Silicon-based equivalents. But at system level cost parity with Silicon is the goal of the SiC vendors. The SiC power semiconductor market is estimated to $200 million in 2014 and could break the $1.0 barrier by the year 2019. Silicon Carbide will definitely reshape the power electronics industry, especially with applications on mid and high power side (> 1.2kV). SiC offers higher performances i.e. switching frequency, power density, junction temperature and voltage capabilities. According to market researcher Yole, the SiC market, including both discrete devices and modules, could reach $150 million+ in 2015 and about $900 million in 2020, some more conservative figures. This forecast partially depends on whether or not the automotive industry will adopt SiC by 2017-2018.

And this scenario could become a reality. Since 2011 1200 V and higher voltage SiC MOSFETs have been fully released and these MOSFETs are currently being used in automotive for auxiliary power supplies and off-board chargers connected to three-phase power. 650 V to 900 V SiC MOSFETs in development are targeted at automotive OEMs and Tier One suppliers as pre-released products in 2013-14 for primarily on-board drivetrain applications. End of May Toyota announced to implement SiC power devices in their hybrid vehicles. Toyota has developed in collaboration with Denso SiC power semiconductors for use in automotive power control units (PCUs). Test driving vehicles fitted with the new PCUs on public roads in Japan a planned within a year. Through use of SiC power semiconductors fuel efficiency in hybrid vehicles can be improved by 10 percent and reduce PCU size by 80 percent, Toyota underlined. SiC power semiconductors have low power loss when switching on and off, allowing for efficient current flow even at higher frequencies. This enables the coil and capacitor, which account for approximately 40 percent of the size of the PCU, to be reduced in size. However, PCUs account for approximately 25 percent of the total electrical power loss in HVs, with an estimated 20 percent of the total loss associated with the power semiconductors alone. Thus huge loss and space savings can be achieved with the use of SiC power semiconductors. Estimated impact of Cree's novel 900 V SiC MOSFET on specific power and power density in automotive traction inverters at this early stage is limited, but demonstrations elsewhere strongly suggest the potential of obtaining high power densities (well above 20 kW/l) with very high (99 % peak) efficiency (see our cover story in PEE May 2014).

Our cover story in this issue tells another story – Gallium Nitride power semiconductors are rapidly being adopted due to their ability to operate at frequencies and switching speeds beyond the capability of Silicon power devices. With discrete GaN devices capable of switching at slew rates up to 70 V/ns, the system performance is greatly impacted by aspects outside the active power devices, such as high speed gate drivers and printed circuit board layout. This year's sales figures are estimated by IMS/IHS to $50 million to reach $1.0 billion by 2022. GaN technology is enabling entirely new applications. In this article, EPC explores GaN penetration in four of these new applications - envelope tracking, wireless power transfer, LiDAR, and satellites. We also discuss GaN's penetration in the original target market, DC/DC conversion. The overall conclusion is that GaN is creating markets that are as large as the markets where they are displacing their Silicon ancestors. GaN devices are expected to re-enact the famous Moore's Law in the coming years, expanding beyond discrete transistors into a variety of integrated circuits with high performance, low cost, and very high value. This drives a "virtuous cycle" where each subsequent generation has increasingly higher performance and lower cost, thus enabling even more new, unforeseen applications.

More on SiC/GaN and other topics of interest within the power electronics industry can be found in our PCIM Report as well as on the other pages. Enjoy reading!

Achim Scharf
PEE Editor

Shift in PV Businesses

Seven of the world's top 10 solar module suppliers in 2013 have their headquarters or the bulk of their manufacturing operations in China, based on IHS (**www.ihs.com**) data of 150 leading PV component manufacturers. Leading the way is China's Yingli Green Energy, which shipped 3.25 GW of solar modules, followed by Trina Solar, Canadian Solar, Sharp and Jinko Solar. "The year 2013 marked the turnaround of global PV markets and the recovery of leading players in the photovoltaic industry," said Jessica Jin, analyst for the solar supply chain at IHS. "Chinese and Japanese PV module suppliers benefited from the surge in demand in their domestic markets, with China in particular accounting for more than a quarter of global installations in 2013 and becoming the leading region in the process." Despite the continued success of China, the country's dominance of global module markets is showing temporary signs of cracking as the overall market share of Chinese suppliers stagnated in 2013, remaining at nearly the same level as in 2012. This comes in contrast to the Japanese, who managed to expand their total share of market last year.

Global PV module shipments grew overall by 24 % in 2013, reaching a total of 38.7 GW. But the top 15 module suppliers expanded their shipments by a noteworthy 43 % on average, which illustrates their solidifying hold on the market. The combined market share last year of the top 15 equated to 59 %, up from 51 % in 2012. The latest module-supplier rankings also reflect the current photovoltaic boom in Japan, which accounted for 17 % of global installations in 2013. Both China and Japan are difficult to enter for foreign companies. However, foreign suppliers in Japan have a better opportunity to sell modules in that country through local partners, OEM production or distributors. Among the PV module suppliers, Chinese-based ReneSola more than tripled its shipments, while South Korea's Hanwha Q-Cells and Japan's Kyocera doubled shipments compared to 2012 levels. Two players - JA Solar from China and Solar Frontier from Japan - grew much faster than the market, with shipments for each expanding by more than 60 %. The REC Group from Norway defended its position as the leading module supplier headquartered in Europe, despite growing somewhat slower than the overall market. "Although the industry is witnessing a long-term trend to more regionalized PV production, the current installation boom in China and Japan is triggering capacity expansion in 2014, predominantly in China," said solar analyst Stefan de Haan.

With many European PV inverter players looking for new opportunities in the US to counteract their ailing business in Europe, the number of suppliers holding a significant share of the US market increased during the year. That, in turn, led to a decline in market share of the three largest PV inverter suppliers based in the States. Moreover, the US trailed Japan and China in growth last year. Although it remained among the three largest growth markets for PV inverters in 2013, the US increase in revenue of 10 % was far behind Japans blistering expansion of 140 % and Chinas equally impressive rate of 100 %. Together the three countries generated a total of $1.7 billion more in revenue for 2013 than in the previous year, despite global revenue declining by $60 million. PV inverter revenue in 2013 from the US, China and Japan amounted to $4.1 billion last year, compared to $2.4 billion in 2012.

Top Global Growth Markets and Suppliers for PV Inverters in 2013

	Japan	China	USA
2013 Revenue	1.24 billion	$400 million	$110 million
Year-over-Year Growth (%)	140%	100%	10%
Top Four Suppliers in Revenue	Omron (Japan) TMEIC (Japan) Tabuchi (Japan) Shindengen (Japan)	Sungrow (China) TBEA (China) Emerson Net. Power (China) Chint Power (China)	SMA (Germany) Advanced Energy (USA) Enphase Energy (USA) ABB (Switzerland)

Source: IHS Technology - May 2014

SiC Wafer Grading Structure for High Crystal Quality

Dow Corning (**www.dowcorning.com**) announced that they have established a higher industry standard for Silicon Carbide (SiC) crystal quality by introducing a product grading structure that specifies new tolerances on killer device defects, such as micropipe dislocations (MPD), threading screw dislocations (TSD) and basal plane dislocations (BPD).

This new grading structure aims to optimize the range, performance and cost of next-generation power electronic device designs fabricated on 100-mm SiC wafers, which the company now offers in three new tiers of manufacturing-quality substrates labeled Prime Standard, Prime Select and Prime Ultra. Each successive Prime Grade wafer tier offers tighter tolerances for defect density and other critical performance properties that allow to precisely balance wafer quality and price, depending on the demands of their specific device applications. While many SiC substrate manufacturers promise low micropipe densities, Dow Corning specifies low tolerances of other killer defects, such as TSD and BPD. Such defects reduce device yields, and inhibit the cost-efficient manufacture of large-area, next-generation power electronic devices such as SiC MOSFETs with higher current ratings.

The Prime Grade portfolio includes Prime Standard SiC wafers that guarantee MPD of 0.5 cm^{-2} or less, offering an attractive option for balancing performance and cost when designing simpler SiC power electronic components, such as Schottky or Junction Barrier Schottky diodes, with low to medium current ratings. Prime Select SiC wafers that deliver more stringent tolerances for MPD ($\leq$0.2 cm^{-2}) and BPD ($\leq$800 cm^{-2}), making them suitable for more demanding SiC devices like pin diodes or switches. Prime Ultra SiC wafers enable design of high-power devices that require the highest crystal quality. SiC substrates in this tier deliver extremely low MPD ($\leq$0.1 cm^{-2}), BPD ($\leq$500 cm^{-2}), TSD ($\leq$300 cm^{-2}) and a tightened wafer resistivity distribution for the design of today's most advanced SiC power electronic devices. These include MOSFETs, JFETs, IGBTs, BJTs or pin diodes. In addition, the substrate quality in this tier can benefit high-voltage (3.3 kV and higher) and high-current device designs. "We recognized that wide-bandgap semiconductor technology must deliver much more than high quality alone – it must deliver exceptional overall value," said Dow Corning's CEO Gregg Zank. "Our new SiC wafer grading structure meets this need and is the result of our close collaboration with the globe's leading power electronics device manufacturers".

Silicon Carbide Market Moves from Discretes to Modules

Silicon Carbide will definitely reshape the power electronics industry, especially with applications on mid and high power side (> 1.2kV). SiC offers higher performances i.e. switching frequency, power density, junction temperature and voltage capabilities.

"Originally, the SiC industry began from a discrete device business and is today moving into a power module business", analyzed Kamel Madjour, technology and market analyst at Yole Développement (**www.yole.fr**) at PCIM. Initially, the first innovative companies started to implement hybrid Si/SiC products (power modules, PV inverters…), then other players reached the market with full-SiC modules. This trend will become dominant in the coming years as integrators require SiC power modules in most of their mid and high power systems. The SiC market, including both discrete devices and modules, could reach $150 million+ in 2015 and about $900 million in 2020. This forecast partially depends on whether or not the automotive industry will adopt SiC by 2017-2018. More on SiC and GaN in our PCIM Europe 2014 report.

300 Millimeter Wafers Pay Off

Infineon is the first to manufacture MOSFETs and IGBTs on 300-millimeter Silicon wafers as demonstrated by CEO Reinhard Ploss Photo: AS

Infineon (www.infineon.com) is beginning to reap the fruits of 300-millimeter thin-wafer technology for power semiconductors, enabling it to achieve growth with a substantially lower level of capital employed compared with 200-millimeter wafers. The level of investments required to increase manufacturing capacities for power semiconductors in order to achieve the targeted growth rate is therefore decreasing.

With effect from the 2015 fiscal year, the company intends to reduce its target ratio of investments to revenue over the cycle from the current about 15 percent to about 13 percent. Even with the reduced capital intensity, it will still be possible to achieve the targeted average revenue growth rate of approximately 8 percent p.a. over the cycle. "Infineon is determined to grow faster than its competitors. The fact that we will need to employ less capital in future to achieve this, clearly demonstrates that we are on the right track with our manufacturing strategy", stated Dr. Reinhard Ploss, CEO of Infineon Technologies AG.

Transphorm licenses Furukawa GaN Patents

Transphorm (www.transphormusa.com) has obtained a sole license to Furukawa Electric (Japan) extensive Gallium Nitride (GaN) power device portfolio that includes approximately 40 US issued patents and 110 Japanese issued patents. Transphorm also has certain rights to sublicense these patents.

The licensed patents encompasses various aspects of GaN power device manufacturing, materials and circuits, including key patents for GaN-on-Silicon epitaxial growth technology. As part of the agreement, Furukawa Electric also made an equity investment in Transphorm. The deal brings Transphorm's total GaN IP portfolio to over 300 US patents/applications and over 650 worldwide patents/applications, including a combination of internally developed, acquired and licensed patents. "Furukawa Electric has conducted original GaN research starting from the 1990s and amassed a strong patent portfolio in GaN power devices and materials," said Takahide Kimura, Corporate Senior VP Furukawa Electric. "As we sought to unlock the value of this portfolio, as well as to secure a supply of GaN products for our own applications, this company appeared as an ideal choice. Additionally, we will have further technical collaboration with them as a strategic partner, beyond this license and investment". "As GaN power devices are now poised for rapid market penetration, a strong intellectual property position is essential to growing the GaN business", added Roger Borovoy, Transphorm's IP counsel.

Product Compliance Ltd. launch their Compliance Management Service for the Power Electronics sector.

Product Approvals Ltd. offer a Compliance Management Service which fulfils the compliance requirements for companies in an economic and timely way. Product Approvals Ltd. is staffed by compliance specialists with many years of experience between them and diverse product management, engineering and regulatory expertise.

Compliance specialists are difficult to find and are often seen as an unnecessary overhead by businesses. This results in inexperienced staff being given the compliance work as a second "job" or worse still, it gets ignored until a problem arises with the regulatory authorities.

Many manufacturers are finding that the route to increased sales is by exporting to Europe and beyond. These major export markets have diverse technical and regulatory requirements which present major hurdles to companies exporting to those regions.

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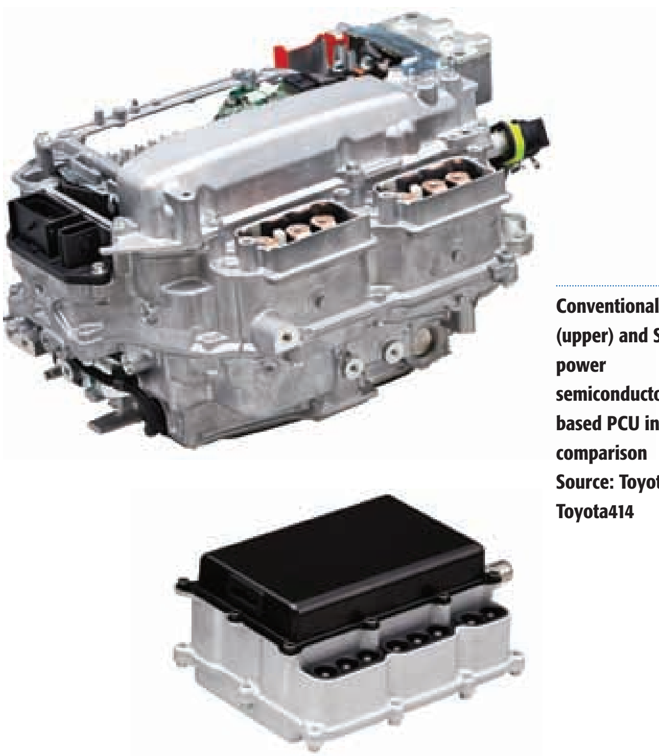
Toyota uses SiC in Automobiles

Toyota (**www.toyota.co.jp**) has developed in collaboration with Denso a SiC power semiconductor for use in automotive power control units (PCUs). Test driving vehicles fitted with the new PCUs on public roads in Japan a planned within a year.

Through use of SiC power semiconductors fuel efficiency in hybrid vehicles can be improved by 10 percent and reduce PCU size by 80 percent. SiC power semiconductors have low power loss when switching on and off, allowing for efficient current flow even at higher frequencies. This enables the coil and capacitor, which account for approximately 40 percent of the size of the PCU, to be reduced in size.

PCUs play an important role in hybrids and other vehicles with an electrified powertrain: they supply electrical power from the battery to the motor to control vehicle speed, and also recuperate electricity during deceleration. However, PCUs account for approximately 25 percent of the total electrical power loss in HVs, with an estimated 20 percent of the total loss associated with the power semiconductors alone. Therefore, a key way to improve fuel efficiency is to improve power semiconductor efficiency, specifically by reducing on-resistance. Since launching the "Prius" HV in 1997, Toyota has been working on in-house development of power semiconductors and on improving HV fuel efficiency.

As SiC enables higher efficiency than Silicon, Toyota and Denso began basic research in the 1980s, with Toyota participating from 2007 to jointly develop SiC semiconductors for practical use. Toyota has installed the jointly developed SiC power semiconductors in PCUs for prototype HVs, and test driving on test courses has confirmed a fuel efficiency increase exceeding 5 percent under the JC08 test cycle. In December last year, Toyota established a clean room for dedicated development of SiC semiconductors at its Hirose Plant. Toyota is positioning high efficiency power semiconductors as a key technology for improving fuel efficiency for HVs and other vehicles with electrified powertrains.



Conventional PCU (upper) and SiC power semiconductor based PCU in size comparison Source: Toyota Toyota414

Another Power Electronics Conference for Holidays on Hawaii

ISPSD is the next forum on the calendar for technical discussion in all areas of power semiconductor devices and power integrated circuits. ISPSD'14 will be held from June 15-19 at the vacation resort, Hilton Waikoloa Village, located on the Kohala Coast of the Big Island of Hawaii, and thus will perhaps of interest for those not able to attend APEC, CIPS, or PCIM. More than 400 delegates are expected to take this opportunity.

The conference features 110 technical presentations on novel GaN, SiC, and Silicon power device concepts, process integration, device modeling, power ICs, packaging and integration, and power electronics applications. A vendor exhibition includes Azzurro Semiconductors AG (Germany), DCG Systems, FEI Company Japan Ltd., Marubun Corp., New Metal and Chemicals Corp. Ltd., and TowerJazz Japan Ltd.

Three plenary talks by renowned experts on

- Power Architectures for Current and Future High Performance Computers, Dr. Paul Coteus, IBM Fellow, USA
- Virtual Testing of High Power Devices at the Rim of Safe Operating Area and Beyond, Prof. Gerhard Wachutka, Munich University of Technology, Germany
- Very High Power Converter Technologies, Dr. Shinzo Tamai, Senior Fellow, Toshiba Mitsubishi-Electric Industrial Systems Corporation (TEMIC), Japan

Six 'short courses' will provide an overview on the recent debates on Silicon versus SiC and GaN or their coexistence

Integrated voltage regulators: Bringing Moore's Law Scaling to Power Electronics, Prof. Ken Shepard, Columbia University

Computation and communications ICs demand an increasing number of supply voltages, due to heterogeneous circuitry and the need to dynamically adjust supply voltages to optimize power-performance trade-offs. Today, the dc-dc converters that deliver these supply voltage sit on the printed-circuit board and are built from discrete components. This approach results in an ever increasing fraction of board area (and cost) allocated to DC/DC converters. Off-chip regulators are also slow to respond to changing load requirements. Because of these shortcomings, there is a growing interest in integrating DC/DC converters. There are several approaches that can be taken, including package-level integration, 3D integration, and monolithic integration, all of which will be reviewed in this short course. Key to these efforts is reducing the physical size of the energy storage elements required for DC/DC converters. This lecture will review recent advances in both switched-capacitor and switched-inductor converters. Integrated switched-inductor converters, which bring many advantages over switched capacitor designs, require integrated power inductors. The presentation will describe recent advances that allow power inductors to be integrated quite effectively in the far back-end of a conventional CMOS process.

Are SiC Switches Ready for High Power Industrial Applications?
Dr. Ljubisa Stevanovic, GE Global Research

This short course describes challenges of expanding the adoption of SiC MOSFETs from technical (high density and high precision) applications, such as aerospace, to high power industrial applications, including renewables. Typically, technical applications prioritize performance ahead of all other requirements, demanding higher switching frequency, power density and operating temperature. The presentation describes SiC devices and power packaging that are designed to maximize performance in such applications. Industrial applications are less cost-tolerant and require higher reliability, preventing SiC from making significant inroads to date. While the device cost continues to improve with volume and yield, it is necessary to unlock significant system-level savings in order to reach cost parity with Silicon-based solutions. Device/module reliability has been an even bigger challenge. With a high number of devices per module/converter, it is necessary to achieve device failure rate below 10 FIT, while maximizing power output. There is no evidence that commercially available SiC switches have demonstrated such FIT rates. Ongoing efforts to validate the device and package reliability will be highlighted, including accelerated stress testing, qualification per AEC-Q101 and reliability growth testing. The presentation will conclude by highlighting module and converter-level test results as part of a megawatt-scale industrial converter demonstration.

Heterogeneous Integration of GaN and Si CMOS: A Path to "Smart" Electronics, Dr. T. E. Kazior, Raytheon Integrated Systems

Advances in Silicon technology continue to revolutionize electronics. However, Si cannot do everything, and devices/circuits based on other material systems are required. Can we take advantage of the maturity and integration density of Si and integrate these 'other' devices with CMOS control circuitry to create 'smart' circuits that further enhance system performance? This short course will review different approaches for integrating dissimilar devices/materials with Si CMOS Emphasis will be given to the successful integration of GaN HEMTs with Si CMOS on a common Silicon substrate using a process similar to a SiGe BiCMOS fabrication process. Using this approach, circuit performance can be optimized by the strategic placement of high performance GaN transistors adjacent to Si CMOS cells or in-situ controllers. The devices and subcircuits may be interconnected using standard semiconductor on-wafer interconnect processes. This GaN – Si CMOS integration process is capable of scaling to 200 mm diameter wafers to take advantage of existing Si foundry infrastructure and provide a cost effective solution. Thus, heterogeneous integration of GaN with Si CMOS may enable a new class 'smart' RF, mixed signal and power ICs.

Photovoltaic Systems: Technology trends and challenges through to 2020, Dr. Asim Mumtaz, Enecsys Corporation

The short course will cover some of the latest market projections for photovoltaic systems up to 2020. A review of the different architectures for photovoltaic power systems will be presented, with some example topologies. The impact of SiC and GaN power devices and power packaging for performance enhancement will be reviewed. In addition, potential areas for the utilization of ASICs and ASSPs will be highlighted for cost reduction benefits. The latest trends in photovoltaic modules and the changing landscape of the grid utility requirements will also be analyzed. The communication requirements for photovoltaic systems and the utilization of RF semiconductors will be introduced.

Practical ESD Protection Design Technique: from High-Speed to High-Voltage, Prof. Albert Wang, University of California-Riverside

As semiconductor technologies continue to advance andICs become more complex to achieve better performance, ESD protection design has emerged as a major design challenge to IC designers. This is particularly true for complex mixed-signal ICs operating at high-speed and high-voltage. For high-speed ICs, the ESD-induced parasitic effects can severely affect IC performance including speed, bandwidth and data rate. For complex high-voltage ICs, due to the multiple and high-voltage domains involved on a chip, accurate control of the ESD design window is essential and challenging. These emerging challenges call for accurate ESD design and ESD-IC co-design techniques to ensure whole-chip ESD protection circuit design optimization, verification and prediction. This short course will present essential ESD protection design techniques including ESD protection fundamentals, ESD protection structures, ESD design window for high and low voltage, low-parasitic ESD protection designs for broad band and high-speed ICs, ESD protection designs for multi-supply and high-voltage mixed-signal ICs, mixed-mode ESD protection circuit simulation design methods, and new ESD-IC co-design techniques. Real-world ESD protection design examples for high-speed and high-voltage ICs will be discussed.

Power Semiconductor Devices and Modules for Hybrid Vehicles, Dr. Kimimori Hamada, Toyota Motor Corporation

In this short course, the requirements for power semiconductor devices and modules for hybrid vehicle automotive application will be presented. Foundational semiconductor device technologies utilized for existing automotive applications will be presented and power module structures and other supporting packaging technologies will be discussed. Specific examples of simulation methodologies, measurement techniques and power system analysis will be presented to demonstrate the technical evolution of power systems in hybrid vehicles. Through this short course, attendees will understand the specific requirements and technologies required for expanding the presence of power electronics into a growing automotive application market segment. **AS**

On the Road to New Frontiers

PCIM Europe 2014 ended on May 22 with a positive outcome. Approximately 8,000 visitors have come to Nuremberg to inform themselves about new products and services in power electronics, power quality and intelligent motion during May 20-22. In total 391 exhibitors and 97 representing companies exhibited an extensive range of products and services to the trade visitors on an area of 20,000 square metres. At the conference, which took place in parallel to the exhibition, over 700 participants caught up with the latest perspectives and developments of Power Electronics, Intelligent Motion, Renewable Energy and Energy Management sectors.

Again Power Electronics Europe actively participated within this event by co-sponsoring the Best Paper Award (BPA) as well as hosting a Panel Discussion on the hot topic "SiC/GaN versus Silicon – Competition or Coexistence?". The BPA (price money plus expenses for visiting PCIM Asia 2015) was handed over on occasion of the opening ceremony by PEE Editor Achim Scharf (left) to Martel Tsirinomeny from LEI-EPFL Lausanne, Switzerland.

PCIM Awards and Panel

The title of the winning paper: **Configurable Modular Multilevel Converter (CMMC) for a Universal and Flexible Integrated Charging System.** Electric Vehicles owners are confronted by the limited compatibility of available charging infrastructures. Therefore, this paper is focused on presenting a Configurable Modular Multilevel Converter (CMMC) for a universal and flexible integrated charging system. This concept is designed for a large range of charging infrastructure; from AC household basic supply to AC or DC ultrafast charging.

Also the three Young Engineer Awards have been handed over to **Hidekazu Umeda,** Panasonic, Japan, for the paper 'Highly Efficient Low-Voltage DC-DC Converter at 2 – 5 MHz with High Operating Current Using GaN Gate Injection Transistors', **Gang Yang,** Valeo, France, 'High Efficiency Parallel-parallel Interleaved LLC Resonant Converter for HV/LV Conversion in Electric/Hybrid Vehicles', and **Vinoth Kumar Sundaramoorthy,** ABB Switzerland, 'Simultaneous Online Estimation of Junction Temperature and Current of IGBTs Using Emitter-auxiliary Emitter Parasitic Inductance'.

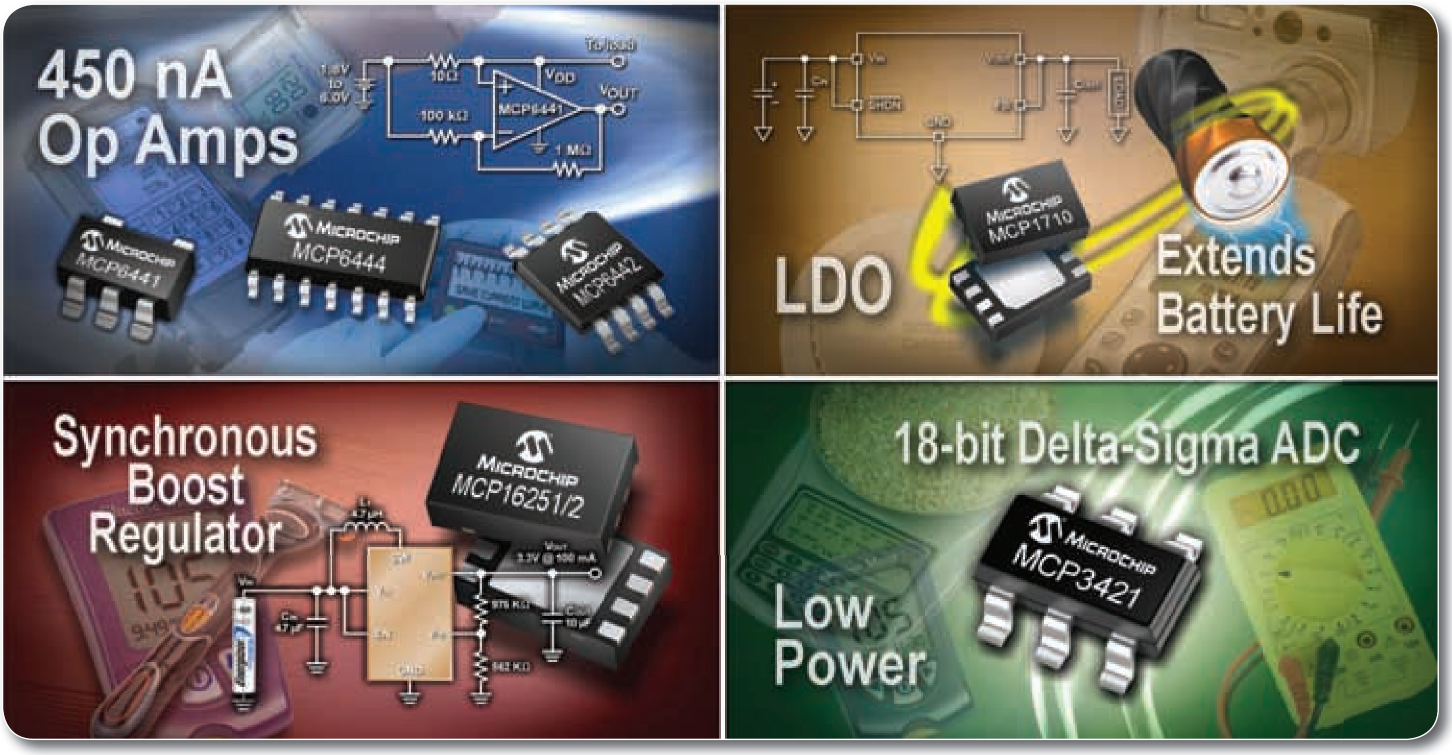
The BPA was handed over on occasion of the PCIM opening ceremony by PEE Editor Achim Scharf (left) to Martel Tsirinomeny Photo: Mesag

PEE's well accepted Panel Discussion **"SiC/GaN versus Silicon – Competition or Coexistence?"** took place on the second day (May 21, 2.00-4.30 pm) in the Industry Forum. Silicon Carbide and more recently Gallium Nitride have gained more and more interest by power electronics designers particularly for inverter and power supply applications. But Silicon technology is still moving forward. Thus the intention of this panel discussion was to inform PCIM visitors about the pros and cons of SiC and GaN in relation to progress in Si also in certain applications such as power supplies and renewable energies, about company-specific technologies and product roadmaps, and last but not least market trends. Thus the panel represented the leading companies in Silicon, Silicon Carbide, Gallium Nitride as well as Packaging Technologies. Silicon Carbide and more recently Gallium Nitride have gained more and more interest by power electronics designers particularly for inverter and power supply applications. But Silicon technology is still moving forward. Thus the intention of this panel discussion was to inform PCIM visitors about the pros and cons of SiC and GaN in relation to progress in Si also in certain applications such as power supplies and renewable energies, about company-specific technologies and product roadmaps, and last but not least market trends. Thus the panel represented the leading companies in Silicon, Silicon Carbide, Gallium Nitride as well as Packaging Technologies.

Panelist were (left to right in the photo) ABB (Munaf Rahimo, Corporate Executive Engineer), Cree (John Palmour, CTO), EPC (Alex Lidow, CEO), GaN Systems (Geoff Haynes, VP Business Development), Infineon (Gerald Deboy, Senior Principal für Power Management & Supply), International Rectifier (Michael Briere, Consultant), Mitsubishi Electric (Gourab Majumdar, CTO/Fellow), Semikron (Thomas Grasshoff, Head Intern. Product Management), Toshiba Europe (Georges Tchouangue, Chief Engineer Appl. Engineering), and Transphorm (Primit Parikh, President). The panel agreed that new power semiconductors will open new business opportunities besides the existing and also growing Silicon markets and that new packaging technologies are necessary to squeeze out the

Does Your Design Require Low Power Analog?

Microchip has the answer ...



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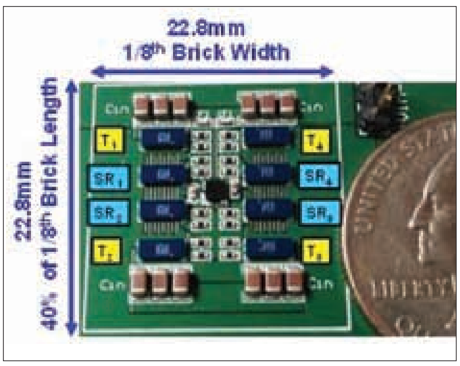
PEE's discussion panelists "SiC/GaN versus Silicon – Competition or Coexistence?" Photo: AS

possibilities of the newly power semiconductors. Due to the interest of the audience the time was exceeded by 30 minutes to a total of 2.5 hours.

New Frontiers with GaN

One of the well accepted PCIM Sessions were 'New Frontiers of Power Electronics with GaN' featuring five papers.

David Reusch from EPC (**www.epc-co.com**) opened this session with the paper **'Improving Performance of High Speed GaN Transistors Operating in Parallel for High Current Applications'.** The objective of paralleling devices is to combine multiple higher on-resistance devices to appear and operate as a single, lower on-resistance device allowing for higher power handling capability. To effectively parallel devices, each device should equally share current



Four parallel GaN transistor layout with four distributed high-frequency power loops Source: EPC

dynamically, and in steady state, and equally divide switching related losses. The introduction of unbalanced in-circuit parasitics between parallel devices leads to uneven sharing and degraded electrical and thermal performance, limiting the effectiveness of paralleling. For high speed devices such as GaN FETs, the increased switching speeds amplify the impact of parasitic mismatches. Thus this paper studied the impact of in-circuit parasitic imbalances on parallel performance for higher speed GaN devices. A background of the impacts of the common source inductance, high frequency loop inductance, and gate inductance on switching performance was also included (see also our cover story).

To improve the parallel performance of high speed GaN devices also the parasitic imbalance contributed by the PCB layout must be minimized. This work looked at different parallel layouts and assess their ability to provide parallel performance similar to an optimized single transistor design. Different parallel designs were created, each containing four devices in parallel and operating from 48 V to 12 V at a switching frequency of 300 kHz. In total, eight 100 V EPC2001 eGaN FETs were used to achieve output power up to 480 W.

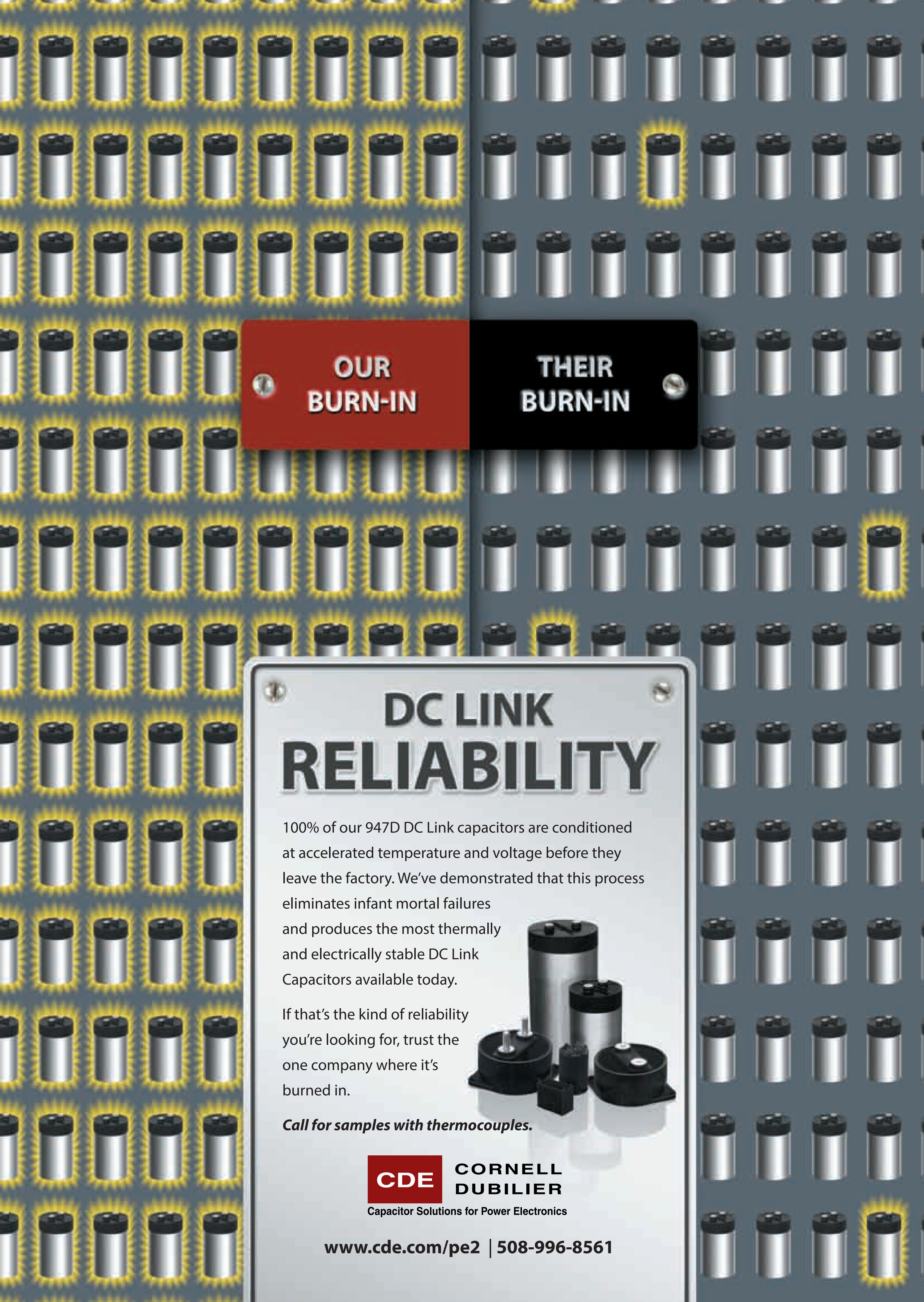
Larry Spaziani from Canadian GaN Systems (**www.gansystems.com**) spoke about 'Lateral GaN Transistors – A Replacement for IGBTs in Automotive Applications'. The current drive-train power requirements of most hybrid vehicle (HV) and electric vehicles (EV) are met by using Silicon IGBT devices. Higher performance can be achieved with GaN power transistors because they can provide lower on resistance, higher operating temperatures and smaller systems. The improvements offered by the GaN devices are yet to be realized in deployed subsystems. Several groups of researchers are experimenting and reporting upon GaN transistors that are aimed at replacing Si IGBTs. The results

achieved by GaN Systems were presented. Shown were the package types used by IR/Delphi and GaN Systems. GaN Systems designs use a source sense electrode and no bond wires. This ensures that the devices can be driven cleanly, on-and-off, and free of source power electrode generated noise. "Market researchers forecast a HEV power module market of $3.5 billion in 2020. Through multi-level converters requiring 1200 V in automotive applications GaN devices might be feasible", Spaziani pointed out.

David C. Sheridan from RFMD (**www.rfmd.com**) presented 'Ultra-Low Loss 600V – 1200V GaN Power Transistors for High-Efficiency Applications' based on SiC substrates. While 650V is likely the first entry for GaN power devices, 1200V GaN switches have not been widely reported. Using the same base technology as the 650 V products, 1200 V die were fabricated with breakdown voltages exceeding 1500 V as suitable margin for over-voltage protection. Since superjunction technology is not yet capable of 1200 V devices, the switching performance was compared to similarly rated 1200 V SiC MOSFETs which have already shown performance advantages over Si IGBTs. Bi-directional power devices have been a continuing topic of research and device design to enable specific topologies and applications such as matrix converters for direct AC/AC conversion.

A normally-on GaN device has no barrier to current flow in both forward and reverse direction and can be configured efficiently into a bidirectional switch with each blocking mode sharing the same drift region.

Panasonic's (**www.jp.panasonic.com**) Tatsuo Morita presented a '99.3 % Efficiency of Boost-up Converter for Totem-pole Bridgeless PFC Using GaN Gate Injection Transistors'. In this paper, a highly efficient operation of a boost-up converter for bridgeless PFC using normally-off GaN Gate Injection Transistors (GITs) in a novel totem-pole output circuitry has been introduced. The normally-off device by a single chip with flip-chip assembly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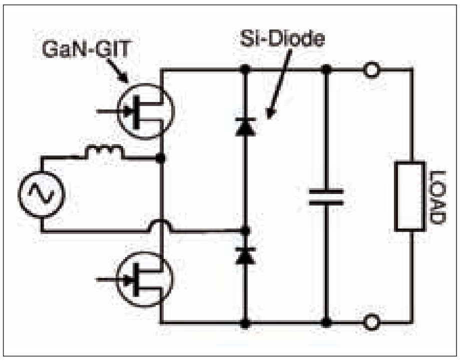


Proposed Totem-pole PFC with Panasonic's GaN GITs
Source: Panasonic

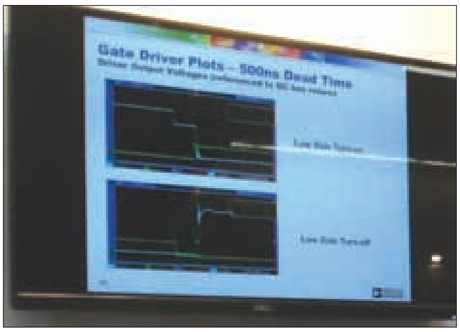
effectively reduces the loop inductance in the circuit. The fabricated boost-up converter exhibits peak efficiency of 99.3% and efficiency of over 99% is maintained in a wide range of output power from 450 W to 2 kW. The maximum output power of 2 kW is the highest ever reported for the efficient boost-up converter.

Eric Persson from International Rectifier (**www.irf.com**) spoke about GaN benefits in low-frequency motor drives. Appliance motor drives are often operated at low PWM frequencies (6–20 kHz), as there is little benefit to increase the switching frequency above audible frequencies: switching losses will increase with no corresponding reduction in the size of the magnetic (motor) as its size is based on the torque/power requirements. So applying a GaN device capable of switching at much higher frequencies in this application might not appear to make sense at first, but this paper showed that, for a given size power stage, GaN clearly outperforms both IGBTs and Si FETs in conduction loss, switching loss, and EMI, not only at full power but especially at light load.

This is particularly important for compressor motor drives used in refrigeration and HVAC applications, which commonly operate at <25 % of full load. Also the low reverse recovery charge of GaN cascode device, and the correspondingly low hard-switched turn-on current spike significantly reduces the conducted EMI. In conclusion - drive applications, particularly at light load, can benefit from the 9x improved Qrr of the GaN cascode over IGBT antiparallel diode, and 160x improved over Silicon FREDFET – and its independence of temperature. This results in a significant improvement in efficiency, and an overall reduction in conducted EMI. The reduced dissipation allows higher power density and enables further integration of the inverter into a monolithic GaN device for extremely high power density.

Drives for Power Devices

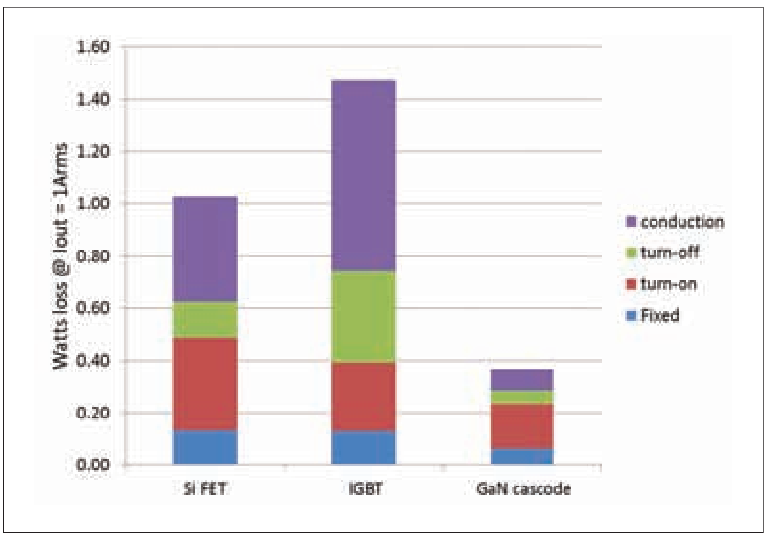
Bernhard Strzalkowski from Analog Devices (**www.analog.com**) stressed isolation issues in his paper 'Maximum power limit for withstand insulation capability of IGBT/MOSFET gate drivers'. The power density of modern power inverter rises continuously. This is due to constantly increasing performances of MOSFETs and IGBTs as well as of the gate drivers. One unpredictable system fault can cause damage or explosion of power switches. On the other hand, new high performance gate drivers exhibit excellent propagation delay, high bandwidth, over-current protection and high



Analog's Gate Driver exhibit 500 ns dead time and high magnetic isolation

integration level. Those drivers provide a small form factor because the electrical isolation is already integrated on the driver chip. This electrical isolation can be performed by means of integrated high voltage micro-transformers or capacitors.

RIGHT Loss components at 200 W output power Source: International Rectifier



Therefore, for high power density inverters, the gate driver isolation safety performance needs to be investigated and validated. The isolation reliability must be analyzed in the worst case, when power-switches destruct. The paper investigated the gate driver's isolation behavior by intentional destruction of IGBT/MOSFET power switches. High-voltage isolation test confirmed withstand of electrical micro-isolation.

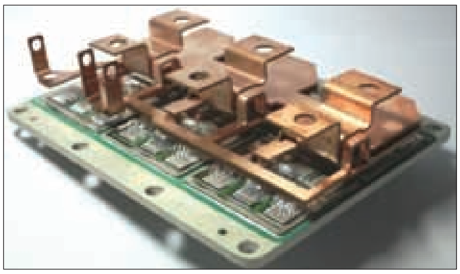
Infineon's (**www.infineon.com/eicedriver**) Wolfgang Frank introduced a novel IGBT driver concept called EiceDriver Safe with his paper 'Online adjustable gate current control IC solves dv/dt problems in electric drives'. The tuning of commutation speed of currents between freewheeling diodes and IGBT plays an important

Econo-Dual IGBT module with mounted EiceDriver Safe
Source: Infineon

role in respect of the EMI behavior of power electronics. High dv/dt means a large stress for the motor winding insulation and motor bearings as well as it causes conducted and radiated interferences with the supply in general. Many works for speed control of IGBT turn-on are known. The paper presented the benefits of a novel gate drive IC which offers an online adjustment feature for dv/dt in respect of the switching waveforms. A control means that countermeasures for reducing the dv/dt (e.g. filters) can be reduced or even skipped, which is an important step towards system cost reduction.

Packaging and Thermal Aspects

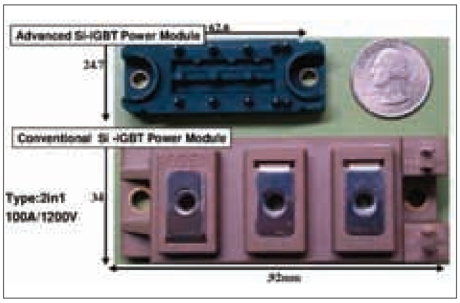
Samuel Hartmann described in the paper 'Packaging Technology Platform for Next Generation High Power IGBT Modules' ABB's (**www.abb.com/semiconductors**) approach for new module layouts. To enable smaller and more cost efficient inverter designs, new power modules are designed for low losses, reliable operation at high temperature, high current and high switching frequencies. The IGBT module design presented features large Silicon active area for low on-state losses, good internal temperature distribution, high current conductor leads with well-designed electro-magnetic behavior and highly reliable joining techniques. While keeping the outline of the HiPak module unchanged the design of the conductor leads and the substrate are optimized. An increase of the active IGBT area by 7 % and of the active diode area by 42 % is achieved. This allows higher output power especially in applications where the diode is normally limiting. The design can also be



Open ABB prototype module for assessing electro-magnetic behavior Source: ABB

used with the reverse conducting Bi-Mode IGBT (BiGT). In this case all chips are dissipating equal thermal power which leads to uneven temperature distribution with the chip arrangement as in the existing HiPak design. With the new design, the temperature distribution is improved by having only 12 chips arranged in the mid of the module.

Fuji's (**www.fujielectric.co.jp**) Motohito Hori announced a novel 'Compact, Low Loss and High Reliable Next Generation Si IGBT Module with Advanced Structure'. To achieve the further miniaturization of power modules, low thermal impedance of the whole module structure is needed, i.e. through thick copper foil on the DCB substrate. This thick copper pattern contributes to reduce the thermal impedance. The advanced structure was researched originally for the small

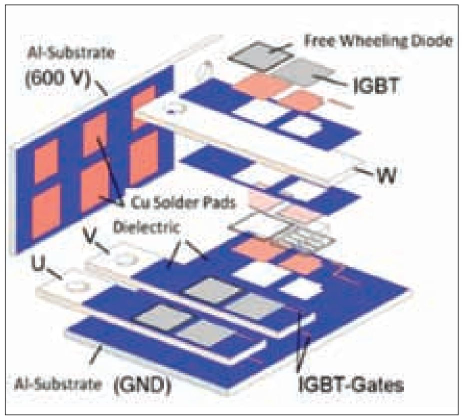


Cross section and exterior view of Fuji's advanced Si IGBT power module Source: Fuji Electric

size of next generation devices such as SiC and allowed for about 30% shrinked chip size compared with conventional structure. Thanks to this improvement, same current and voltage rated Si IGBT power module features about 50 % footprint size of conventional power module at higher power and thermal cycling capability.

With the paper 'Hybrid substrate - A future material for power semiconductor modules' Curamik's (**www.curamik.com**) Xinhe Tang introduced a hybrid substrate comprising of copper, ceramic and aluminum that combines the thermal and electrical performance of the copper with the corrosion resistance of aluminum. The manufacture process has been developed by bonding aluminum to DBC using an adhesive. The aluminum side can be directly contacted to water to improve cooling efficiency without worry about corrosion. The performance and reliability testing are undertaken.

Robert Christopher Burns from AB-Mikroelektronik (**www.ab-mikro.at**) showed in the paper 'Vertical Integration Power Modules for Double Sided Cooling Applications using Aluminum Conductors and Thick Film Dielectrics' possibilities for 3D integration. Challenges, advantages, and manufacturability of a vertical chip stacked power module for double sided cooling applications by using low cost materials and flexible processes.



Exploded view of proposed vertical chip stacking architecture Source: AB Mikroelektronik

Vertical stacked power modules can be cooled on both sides reducing the overall thermal resistance which directly impacts the power per area. Using aluminum conductor plates in combination with thick film dielectrics allows for a compact, cost effective, and light weight power module which makes this technology a great choice for applications where high performance at a low cost is required.

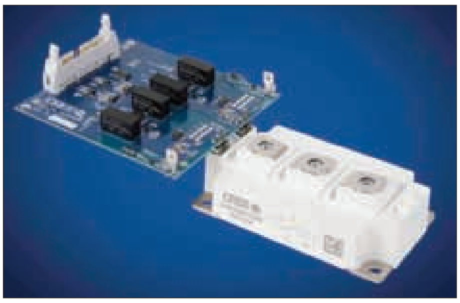
Exhibition Product Innovations

Avago (**www.avagotech.com**) displayed the implementation of Amantys (**www.amantys.com**) Power Insight™ protocol with Avago's 50 MBd Versatile Link™ transmitters and receivers. The combined solution enables an IGBT gate driver with intelligent optical link management and on-board condition monitoring and diagnostics capabilities. It optimizes system power efficiency, cost and availability for inverters targeting renewable energy, industrial motor drive

Amantys' IGBT driver Power Insight™ protocol runs over Avago's 50 MBd Versatile Link™ transmitters and receivers

and transportation applications. Amantys Power Insight provides several important capabilities including monitoring of key system parameters at the IGBT switch during system operation, reporting back detailed fault codes which help the system operator understand the nature of problems in the switch, and configuring the switching characteristics of the IGBT module remotely to match operational demands. "Our vision is to improve the availability and reliability of power systems through the intelligent control of power," commented Erwin Wolf, CEO at Amantys. "Avago Technologies has been supplying Versatile Link products to the power electronics industry for more than two decades," said Martin Weigert, VP of Avago's Industrial Fiber Product Division. "As real-time condition monitoring, diagnostics and adjustment are becoming increasingly important we will continue to enhance our link products with innovative features to improve system efficiency."

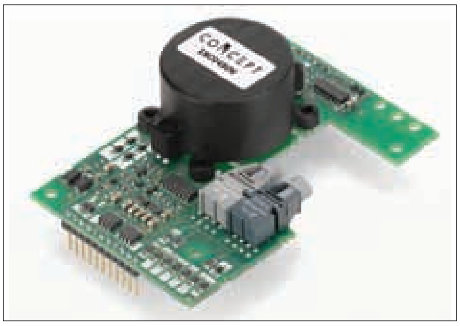
Cree (**www.cree.com/power**) announced a new 40 mΩ, 1200 V SiC MOSFET and a 300 A, 1200 V half-bridge power module aimed at expanding applications in solar and industrial inverters as well as EV chargers and three phase power supplies for induction heating and other industrial automation systems. In addition, Cree introduced a low current 280 mΩ, 1200 V MOSFET to bring SiC advantages



Cree's new 62-mm full-SiC half-bridge power module with driver board

to server, telecom, industrial and LED lighting power supplies. The latest SiC power module (**www.cree.com/power/CAS300M12BM2**) is available with multiple gate driver options and is pin compatible to standard 62-mm half-bridge modules, including IGBT modules rated at 450 A or more. "This new power module is yet another example of our commitment to the commercialization of SiC-based power electronics," said Cengiz Balkas, VP Power and RF. "Utilizing our experience in SiC power devices, we have extended the benefits of SiC power modules to the 100 kW to 1 MW power range for applications such as induction heating, central solar inverters and active front-end motor drives. These new power modules are introduced at a breakthrough price-performance point below $500 that unlocks cost savings in these applications". At display were also reference designs for a 50 kW solar inverter and a high-speed ZVS DC/DC converter.

IGBT gate driver manufacturer CT-Concept (**www.IGBT-Driver.com**) announced the 1SC0450V single driver core for IGBT modules



CT Concept's driver core for IGBT modules with blocking voltages of 4.5 kV and 6.5 kV

with blocking voltages of 4.5 kV and 6.5 kV. This compact driver enables IGBTs to be paralleled using only one driver core. The 1SC0450V is based on the SCALE-2 chip set and a partial-discharge-free, low-coupling-capacitance, high-voltage DC/DC transformer for test voltages up to 10.4 kV RMS and a partial discharge extinction voltage of 7800 Vpeak. The driver core measures 60 mm x 90 mm x 27.50 mm. "Our family of high-voltage gate driver cores, which includes the 2SC0535T 3.3 kV and 2SC0635T 4.5 kV dual gate driver cores, reduces component count, thereby making designs more compact and reliable", said System Engineering Director Michael Hornkamp. "These gate driver cores are suitable to drive all 4.5 kV and 6.5 kV IGBT modules currently available on the market. Target markets include traction and other high-voltage applications."

GaN Systems (**www.gansystems.com**) announced five new normally-off 650 V GaN transistors. The GS66502P, GS66504P, GS66506P and GS66508P are respectively 8.5 A/165 m?, 17 A/82 m?, 25 A/55 m? and 34 A/41

GaNSystem's CEO Girvan Patterson introduced 650 V GaN FETs **Photo: AS**

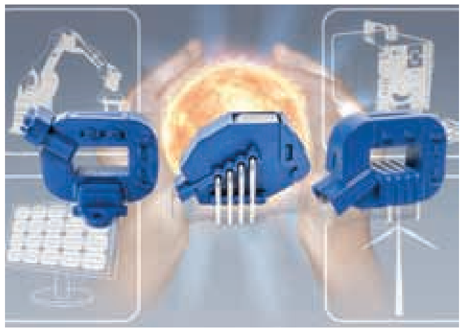
m? parts, while the GS43106L is a 30 A/60 m? cascode. The new 650 V enhancement mode parts feature zero reverse recovery charge and are delivered in near chipscale PX package which eliminates wire bonds. "With these new 650 V parts as well as our recently-announced 100 V family we offer a wide range of parts which are available for sampling now. Applications include high speed DC/DC converters, resonant converters, AC motor drives, inverters, battery chargers and switched mode power supplies", President Girvan Patterson stated.

Infineon's (**www.infineon.com/power**) High Power IGBT Modules (IHM) can be used even longer in the near future. More robust construction and greatly improved thermal conductivity behavior increase the average life time in comparison to previous models by a factor of up to 11 under the same conditions of use. The significantly longer life time of the IHM-B Enhanced modules is based on two central modifications. First of all, a newly implemented manufacturing technology enables more robust bond wire connections. This increases the resilience of the module components in power cycling associated with switching. The power cycling behavior of the IHM-B Enhanced has improved by a factor of two compared to the previous model. Secondly, the thermal conductivity is increased by the combination of an AlSiC base plate with AlN substrates. Depending on the topology the thermal resistivity drops by 16 – 18 %. "With the IHM-B Enhanced modules we are introducing a new manufacturing technology and a new substrate material. These advances have proven themselves in practical testing since the end of 2012 in challenging applications such as wind mills," said product manager Björn-Christoph Schubart. Volume production is scheduled for August 2014.

International Rectifier (**www.irf.com**) introduced a new generation of SIP (System-In-Package) IPMs which shrinks and simplifies the design of appliance motor drive applications including air conditioners, fans, compressors and washing machines. These IPMs feature trench IGBTs and a three-phase gate driver IC plus thermo-mechanical technology to further improve thermal performance and system efficiency by delivering increased power density and enhanced reliability. The new devices are pin-to-pin compatible with the existing IRAM SiP1A series. "Improving the previous IRAM generation was not an easy task. However, the new IRAM platform utilizes state-of-the-art technology for intelligent power modules to address the growing demand for more efficient motor drives", IR's director of IGBT Application Engineering, Andrea Gorgerino, pointed out. The company also launched compact IPMs for low power motor drive applications including fans, pumps, air purifiers and refrigerator compressor drives in a compact 12 mm x 29 mm SOP/DIP package. These so-called µIPM family offers a cost effective power solution by leveraging industry standard footprints and processes compatible with various PCB substrates. The family of 32 new devices features high-voltage FredFET MOSFETs specifically optimized for variable frequency drives with voltage ratings of 250 V or 500 V paired with driver IC tuned to achieve balance between EMI and switching losses. The µIPMs offer DC current ratings up to 4.6 A to drive motors up to 150 W without a heatsink and are available in both through-hole and surface mount package options.

IR's Andrea Gorgerino introduced novel IGBT modules
Photo: ASG

LEM (**www.lem.com**) announced the addition of three new HO series of current transducers which extend nominal current measurement up to 250 A and offer a range of mounting options such as PCB or panel or busbar, and integrating the conductor or with an aperture (15 mm x 8 mm).



LEM's HO series current transducers

The mounting options provide of up to three interchangeable mounts: one vertically, one horizontally and one on the busbar when used. HO series current transducers measure DC, AC, and pulsed signals using Open-loop Hall-effect ASIC. The new series offer offset and gain drifts which are up to twice as accurate across the temperature range as the previous generation and have a faster response time of 2.5 to 3.5 µs. Operating from a single supply voltage of 3.3V or 5 V, the HO series can measure up to x 2.5 the primary nominal current and integrate an additional pin which provides over-current detection set at x 2.93 the nominal current. They also provide fault reporting in the event of memory corruption.

Microsemi (**www.microsemi.com/sicmosfets**) introduced its new SiC MOSFET product family with new 1200 V devices, designed for high-power industrial applications where efficiency is critical. These applications include solutions for solar inverters, electric vehicles, welding and medical devices. "Microsemi is well positioned to capitalize on SiC semiconductor market growth. Market Research estimates the SiC semiconductor market will grow 38 percent year-over-year to $5.3 billion by 2022", underlined James Kerr, director of marketing, power discrete products. "Microsemi continues to expand its SiC product portfolio by capitalizing on our in-house SiC fabrication capabilities", added Pascal Ducluzeau, product marketing director, power module products. The 1200 V/40 A and 50 A SiC MOSFETs are rated at 80 mΩ and 50 mΩ on-resistance in both industry standard TO-247 and SOT-227 packages. SiC MOSFETs are also integrated into the company's power modules, which are used in battery charging, aerospace, solar, welding and other high-power industrial applications. The new power modules provide higher frequency operation and improve system efficiency (**www.microsemi.com/sicpowermodules**). The SiC MOSFETs are also complimented by a complete product line of SiC Schottky Diodes. The new 1700V SiC Schottky Diode expands the line beyond the 1200V and 650V. These products are designed with superior passivation technology for ruggedness in outdoor and humid applications (**www.microsemi.com/sicdiodes**).

Mitsubishi Electric Corp. (**www.mitsubishichips.eu**) introduced new hybrid SiC power modules featuring SiC Schottky Barrier Diodes (SBD) and Silicon IGBTs suitable for switching frequencies of more than 20 kHz. The new hybrid SiC power modules are packaged as 2in1 configurations with 1200 V and 100 A (CMH100DY-24NFH), 150 A (CMH150DY-24NFH), 200 A (CMH200DU-24NFH), 300 A (CMH300DU-24NFH), 400 A (CMH400DU-24NFH) or 600 A (CMH600DU-24NFH). All module packages are compatible with existing Silicon-based modules. The 100 A and 150 A modules offer a 30 % reduced internal inductance. Also a 6.5kV IGBT module of the next generation chip set of 7th gen IGBTs and diodes have been announced which are capable of turning off 4500 A. Therefore it is confirmed that the current rating of the new 6.5 kV IGBT module is able to be increased up to 1000 A from 750 A of conventional modules. Besides these offering the company already introduced full-SiC 3.3 kV power modules for traction applications.

ROHM (**www.rohm.com/eu)** demonstrated its new 3rd gen 1200/650 V SiC MOSFETs based on Trench Gate structure technology, marking another development of SiC MOSFET which the company started back in 2010. Compared to conventional planar MOSFETs which have JFET regions increasing the on-resistance, the new MOSFET types only reach about half of the same on-resistance over the whole temperature range while the stability of the Gate oxide film and of the Body Diode remains as high as with 2nd gen SiC MOSFETs. Since the issues regarding oxide

ROHM introduced 1200/650 V SiC Trench MOSFETs of its 3rd generation

breakdown during high drain-source voltage have been overcome, the result is higher reliability and increased current-carrying capability at reduced cell density, and reduced conductivity loss and switching loss. The company already developed SiC planar MOSFETs which have suppressed the degradation of parasitic PN junction diodes when forward current penetrates. Now, the low on-resistance of the trench SiC MOSFETs improves inverter power density and switching. The parasitic body diode shows minimal reverse recovery behavior and degradation caused by its conduction is widely eliminated. Available in TO-247 3L package or bare dies and 1200/650 voltage ratings, on-resistance varies between 22 and 40 mΩ.

In addition to the 600/650 V and 1200 V Semikron (**www.semikron.com**) MiniSKiiP power modules, 1700 V modules with 6-pack and Converter-Inverter-Brake (CIB) circuit topology are now available. The migration from 400/480 V AC to 600/690 V AC voltage levels used in industrial applications becomes increasingly popular in the process industry due to cost savings based on reduction of motor size, cable cross section, max. load current, total power losses, cable voltage drop during normal operating condition, motor start-up current, or feeding transformer size. For the first time MiniSKiiP Spring Technology is available for power ratings higher than 40 kW. The benefits are lower material costs as compared to traditional inverter designs because the expensive bus-baring of the load connectors can be replaced by a cost-efficient PCB connection. In combination with a fast, solder-free assembly, this allows for reducing the system costs by up to 15 percent. The spring contacts make the layout of the printed circuit board (PCB) simpler and more flexible because the PCB does not need holes for soldering pins. The MiniSKiiP Dual's output of up to 90 kW requires higher current-carrying capability of the PCB, which e. g. can be achieved by using a 105 µm standard metal coating on the PCB. This allows for load currents up to 180 A RMS, which used to be reserved for modules with screw mounted busbars so far. The family concept of SEMiX® is expanded by the introduction of the 1200V SEMiX 3p press-fit half bridge IGBT modules for nominal currents of 300 A, 450 A and 600 A in the same housing size. The SEMiX 3p press-fit comes with an optimized internal design, now making 600 A nominal current possible in housing size 3, leading to lower cost per output power. Finally, Press-Fit expands the SEMITOP® product family as an alternative concept to solder mounting. Press-Fit mounting ensures easy and fast mounting of the module and PCB in one step, reducing the assembly time and cost by eliminating the solder process. Regarding SiC in power modules CSO Peter Sontheimer envisions certain applications such as windmills along with sintered die attach and SkiN connectivity.

Chinese Starpower (**www.starpowereurope.com**) took the opportunity at PCIM to enter the European market by opening a logistics center in Cadenazzo (Switzerland). StarPower was founded in 2005 in

StarPower is in a position to offer competitive products on high-quality level," states Managing Director Peter Frey Photo: AS

Jiaxing near Shanghai and presently has 350 employees. The company produces power modules with state-of-the-art production facilities, such as a fully automated production and testing line in compliance with ISO 9001 standard. The product spectrum comprises standard IGBT half-bridge modules in the power range of 600 V, 1200 V and 1700 V up to 500 A as well as 6-pack and 7-pack modules and IPMs. "Owing to the experience and expertise in R & D and industrial production of power electronics modules, StarPower is in a position to offer competitive products on high-quality level," states Peter Frey, Managing Director and founding member of the European subsidiary. Frey brings with him 22 years of sales experience in power electronic modules and systems. "Our sales exceeded $60 million mainly in China with production figures of 150,000 modules per month. Besides the standard modules we have higher power traction modules and also SiC MOSFET activities", added CEO Hua Shen. Chips are supplied from ABB, Infineon and IR, substrates from Curamik, soldering is used for die-attach and wire-bonding for connectivity - thus standard technology. Modules are Econopack/flow pin-compatible.

Toshiba's (**www.toshiba-components.com**) latest 650 V power MOSFETs are based on the company's fourth generation superjunction DTMOS IV deep trench process and are available in seven different compact packages. Devices can be supplied with an integrated fast recovery diode (FRD). Thanks to the DTMOS IV technology, the new MOSFETs combine ultra-low on resistance with reduced die size, leading to very small form factors without power loss penalties. A strong advantage of the DTMOS IV deep trench process compared to a standard superjunction process, is the lower thermal coefficient of on-resistance over temperature. DTMOS IV also minimizes MOSFET output capacitance, and an optimized gate-drain capacitance delivers improved dv/dt switching control. The company also announced a family of low-voltage Trench-MOSFETs based on the U-MOS IX-H process. The new MOSFETs deliver leading FOM and will be initially available in 40 V versions, having a typical on-resistance of 0.7 mΩ and a typical output capacitance of 1930 pF. The TPHR8504PL is supplied in an ultra-miniature SOP-Advance package measuring 5 mm x 6 mm. Target applications include DC/DC converters, synchronous rectification and other power management circuitry where low-power operation, high-speed switching and minimum PCB real estate are needed.

Vicor (**www.vicorpower.com**) announced a new platform of isolated, regulated DC/DC converter modules based on the company's Converter housed in Package (ChiP) platform. This ChiP DCM platform spans DC/DC conversion requirements from 12 V to 420 V input and 12 V to 55 V output. Coupled with FPA and ZVS regulators, these power components enable

Vicor's Rob Russell presented a new generation of bricks optimized for automotive applications Photo: AS

dense, efficient and scalable source-to-load power system solutions. At PCIM two pre-configured ChiP DCMs have been shown. The first is a 4623 (46 mm x 23 mm) 600 W ChiP DCM, with nominal 290 V input and 13.8 V output for applications such as high-voltage Li-Ion battery to 12 V systems. "This is a new generation of bricks optimized for automotive applications", said Rob Russell, VP of Product Marketing. The second is a 3623 (36 mm x 23 mm) 320 W ChiP DCM with 16-50 V input range and nominal 28 V output, optimized for 28 V MIL-COTS systems. ChiP DCMs provide up to 76 W/cm? power density and 93 % efficiency, with parallel array capability of up to eight units. Both ChiP DCMs are available for order today from Vicor and its authorized distributors such as Hy-Line (**www.hy-line.de**).

Vincotech (**www.vincotech.com**) has rolled out a new set of power modules for UPS and solar applications. These flowMNPC 4w 2g come in flowSCREW 4w housings and feature MNPC topology. The 400 A and 600 A devices have been equipped with a different class of 1200 V and 650 V IGBTs and diodes to improve efficiency and optimize inverters and are also available with a thermal interface made of phase-change material.

Mitsubishi's latest 6.1 generation IGBTs and diodes in the half-bridge path, paired with 650 V semiconductors in the neutral clamp path, improve the performance in the target applications. Featuring a power PCB design, the modules' commutation inductance is very low so no snubber capacitors are needed. Additionally new SiC-based modules featuring SiC MOSFETs have been introduced in two versions. One is a flow3xPHASE 0 SiC three-phase inverter module with 3x BUCK/BOOST and split output topology; the other is a flow3xBOOST 0 SiC with three-channel boost circuits. "At switching frequencies of 50 kHz and above the use of the SiC MOSFET's internal body diode makes sense", said Werner Obermaier. Director Product Marketing. "We use Cree's and Rohm's second generation SiC MOSFETs in our modules". They achieve >99 % peak efficiency at 64 kHz and are equipped with integrated DC-link 600 V ceramic capacitors. The company now makes use of sintering for the die attach in certain modules. "Though the market faces ups and downs, we steadily gained market share over the years. The downturn in photovoltaics was compensated by industrial applications and we are looking for better results in the foreseeable future", CEO Joachim Fietz pointed out. **AS**

Vincotech's CEO Joachim Fietz expects growing market share in power modules Photo: AS

1500 A Industrial Power Tester

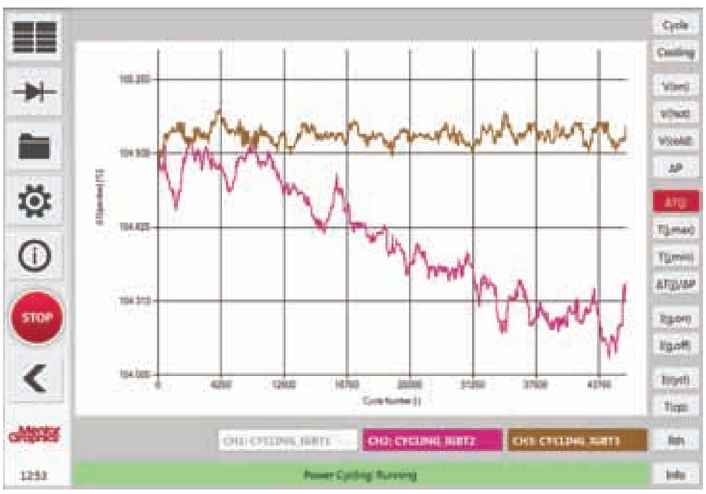
Mentor Graphics introduced at PCIM the Power Tester 1500A for power cycling and thermal testing of electronics components to simulate and measure lifetime performance. The MicReD tests the reliability of discrete power electronic components and modules by combining both power cycling and thermal transient measurements with structure function analysis while providing data for real-time failure-cause diagnostics.

Reliability is a prime concern in many industries that use high-power electronics, so accelerated testing of these modules through a lifetime of cycles is a must for the component supplier, the system supplier, and for the OEM in demanding applications such as off-shore windmills where trouble-

Mentor's new electrical/thermal power tester for discretes and modules

shooting is very costly. For example, railway-traction applications are expected to have a reliable 30-year lifetime, and 50,000 to millions of cycles are required by power modules incorporated into hybrid and electrical vehicles as well as solar and wind turbine energy production systems.

With this increasing pressure, innovation has resulted in new technologies such as ceramic substrates that have an improved heat transfer coefficient, ribbon bonding to replace thick bond wires, and solderless die-attach to enhance the cycling capability of the modules. The new substrates help to decrease temperatures, the ribbons can take more current, and the solderless



Change in junction temp for various IGBTs over cycles

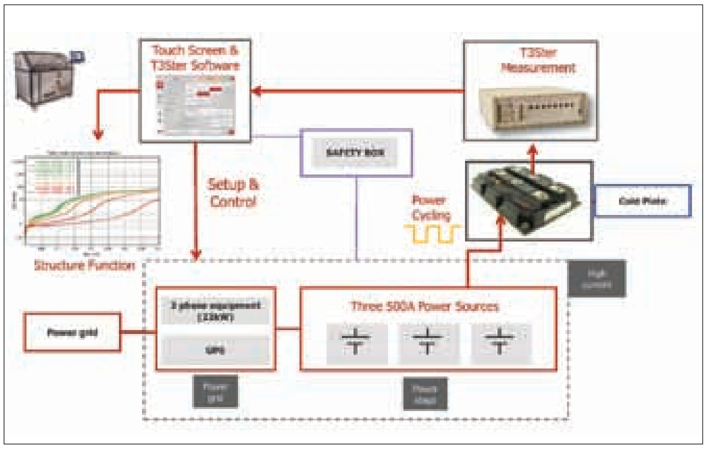
die-attach can be sintered silver which has extra low thermal resistance. In a nutshell, the thermal path has been improved.

However, thermal and thermal-mechanical stress can still cause failures related to power cycling and heat. These stresses can lead to problems such as bond wire degradation, solder fatigue, delamination of stack-ups, and die or substrate cracks.

Test procedure

The MicReD Power Tester 1500A can power modules test through tens of thousands - potentially millions - of cycles while providing "real-time" failure-in-progress data for diagnostics. This significantly reduces test and lab diagnosis time and eliminates the need for post-mortem or destructive failure analysis. Common thermally-induced mechanical failures that the tester analyzes in "real time" include die-attach wire bond separations, die and package stack-up delamination and cracks, and solder fatigue.

While running power cycles, the real-time structure function analysis shows the failure in progress, the number of cycles, and the cause of the



Test procedure for power modules

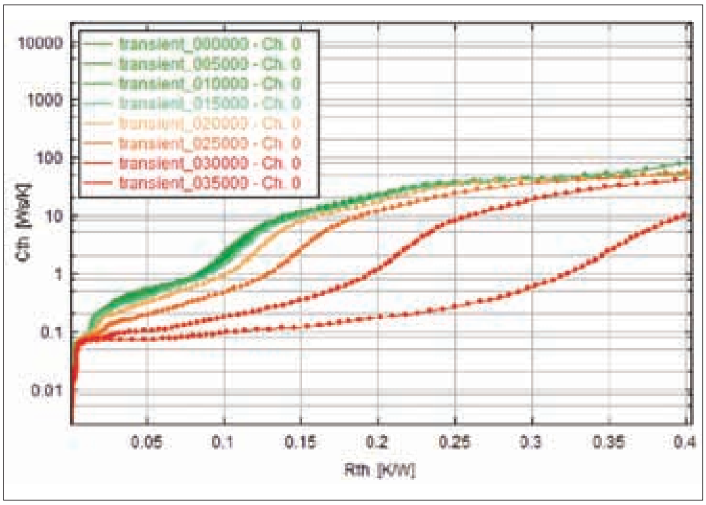
failure, eliminating the need for a lab post-mortem. Conducting lengthy cycling measurements on multiple samples to estimate the cycle count range corresponding to degradation is no longer necessary. Also there's no need for an excess number of thermal measurements in this range to ensure degradation is captured. The device under test only has to be mounted and connected once; cycling and configuration are defined at the start. The testing and characterization data produced can be used to calibrate and validate detailed models in FloTHERM and FloEFD thermal simulation software.

The MicReD Power Tester 1500Ais based on the T3Ster® advanced thermal tester for accurate thermal characterization of semiconductor device packages and LEDs. The MicReD industrial products incorporate the laboratory-level accuracy of the T3Ster product in robust machines for operators to use inside manufacturing facilities. The Power Tester 1500A provides a touch-screen interface and can record a broad range of information during test, such as current, voltage and die temperature sensing; and detailed structure function analysis to record changes in the package's thermal structure. This makes it a platform for package development and quality checking of incoming parts before production, even under unattended operation over weeks.

The Power Tester follows the JEDEC Standard JESD 51-1 static test method. Based on the captured transient response, the system can automatically generate structure functions. Structure functions provide an equivalent model of the heat conduction path expressed by thermal resistances and thermal capacitances, and they can be used to detect structural failures or to capture partial thermal resistances in the heat

Maximum load current	3 x 500 A / 1 x 1,500 A
Pulse current duration	0.5 s onward
Automated k-factor calibration for thermal testing	As many as 3 samples in parallel
Automated failure detection based on	UCE, ΔT_j, T_{jmax}, R_{th} increase
Data recording	UCE before and after switching, ΔT_j, T_{jmax}, T_{jmin}, ΔP, $\Delta T_j/\Delta P$, structure functions, Igate
Gate current measurement range and resolution	200 pA –100 µA , 25 pA resolution
Voltage measurement time base	1 µs

LEFT: Specifications of Power Tester 1500A



Structure functions (structure time points) generated from the thermal transients measured on sample 0 after every 5,000th cycle in the application example

conduction path. The Power Tester also supports the JEDEC Standard JESD 51-14 transient dual interface measurements to determine the thermal resistance from junctiuon to case. The process of combined power cycling and Rth measurement mode creates stress on the device using power cycles, does regular measurement of Rth during the cycling, monitors system parameters such as voltage and current, and automatically increases Rth measurement frequency.

Test example

Mentor conducted tests with four medium-power IGBT modules containing two half bridges to demonstrate the rich data that can be obtained from automated power cycling of the components. The details of these experiments were presented at the 2013 IEEE Electronics Packaging Technology Conference and the 2014 SEMI-THERM Conference.

The modules were fixed to the liquid-cooled cold plate with a high-conductivity thermal pad to minimize the interfacial thermal resistance. The cold-plate temperature was maintained at 25°C throughout the whole experiment using a refrigerated circulator. The gates of the devices were connected to their drains (the so-called magnified diode setup), with each half-bridge powered by a separate driver circuit. Two current sources were connected to each half bridge. A high-current source that can be switched on and off very fast was used to apply stepwise power changes to the devices. A low current source provided continuous biasing of the IGBT, which allowed device temperature to be measured when the heating current was turned off.

An initial set of tests on four samples was conducted using constant heating and cooling times.

Heating and cooling times were selected to give an initial temperature swing of 100°C, at ~200 W with 3 seconds heating and 10 seconds cooling. This most closely mimics the application environment, where degradation of the thermal structure results in higher junction temperature leading to accelerated aging. Of the four devices, sample 3 failed significantly earlier than the others shortly after 10,000 cycles. Samples 0, 1, and 2 lasted longer, failing after 40,660, 41,476 and 43,489 power cycles, respectively. The flat region in the structure functions figure at 0.08 Ws/K corresponds to the die-attach. The structure is stable until 15,000 cycles, but after that point, the degradation of the die-attach is obvious as its resistance increases continuously until the device fails. Again, the immediate cause of the device failure is unknown, but a short circuit formed between the gate and the emitter has been observed, and burned spots could be seen on the chip surface.

"The ability to pinpoint and quantify degradation in the thermal stack for all semiconductor devices during development will greatly assist in the development of cost-optimized packaging solutions currently hampered by package-reliability concerns," said Mark Johnson, professor of advanced power conversion, faculty of engineering, University of Nottingham. "Mentor's Power Tester 1500A should be an invaluable tool for investigating thermal path degradation in all types of power modules."

www.mentor.com/powertester-1500a

Synchronous Regulator for Always-On Applications

Modern automotive and commercial vehicle power management ICs continue to require higher performance. As the power requirements for these applications continues to grow, the available space for power conversion solutions continually shrinks requiring even higher power densities. Furthermore, the required electrical performance criteria of these switching regulators become more demanding. Only 2.5 µA of quiescent current reducing the battery drain associated with always-on systems.

Automotive ($12V_{NOM}$) or commercial vehicle ($24\ V_{NOM}$) applications running from the battery bus require a well regulated output voltage such as 3.3V, even as the input voltage can swing from 3.5 V in a cold crank or stop/start scenario up to 65 V in a load dump scenario. Similarly, high efficiency is of paramount importance as it minimizes thermal design considerations while also maximizing battery run time in hybrids and electric vehicles. For applications such as security, navigation, safety and environmental control which are often required to be always on, minimal quiescent current is critical so as not to drain the battery when the car is parked for long periods of time. Greater than 2 MHz frequency operation avoids noise in critical frequency bands such as AM radio and minimizes the size and cost of external components. Finally very robust short-circuit and over-voltage protection ensures overall system reliability.

The LT8620 is the first synchronous high voltage step-down regulator that has an input voltage range of 3.4 V to 65 V which can deliver up to 2 A to voltages as low as 0.97 V. Its internal synchronous rectification delivers efficiencies as high as 94 % which eliminates any requirements for heat sinks while its Burst Mode® operation requires only 2.5 µA of quiescent current reducing the battery drain associated with always on systems. The LT8620 offers an minimum on-time of 30 ns, enabling it to step-down from 32 V to 2 V with a switching frequency of 2 MHz. Additionally, it operates with only 250 mV (at 1 A) of dropout under all conditions suited for applications which must withstand cold crank or soft-start scenarios.

Operation Principle

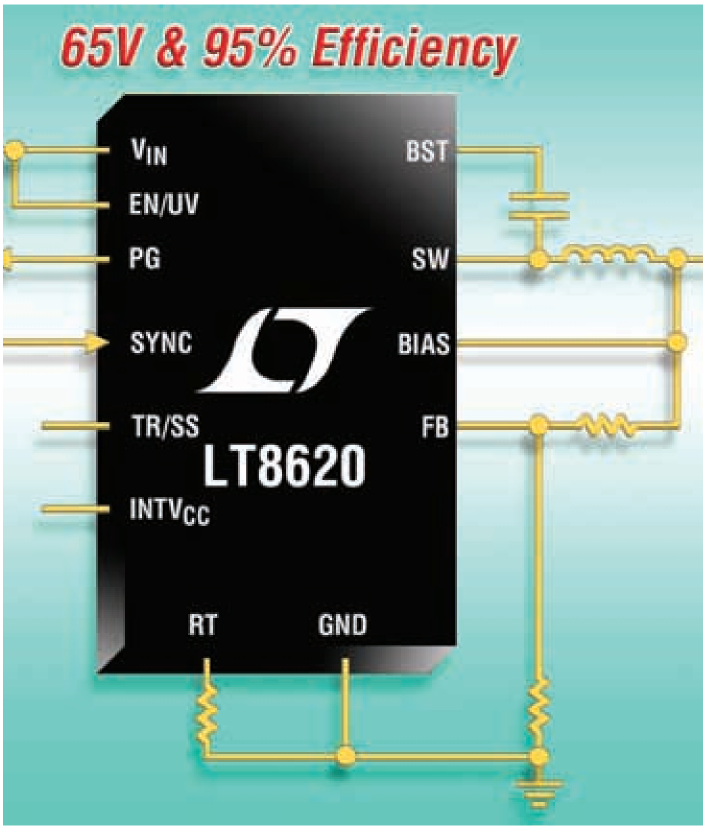
Top and bottom power switches are included with all necessary circuitry to minimize the need for external components. Low ripple Burst Mode operation enables high efficiency down to very low output currents while keeping the output ripple below 10 mV_{P-P}. A SYNC pin allows synchronization to an external clock. Internal compensation with peak current mode topology allows the use of small inductors and results in fast transient response and good loop stability.

The EN/UV pin has an accurate 1 V threshold and can be used to program V_{IN} under-voltage lockout or to shut down reducing the input supply current to 1 µA. A capacitor on the TR/SS pin programs the output voltage ramp rate during start-up. The PG flag signals when V_{OUT} is within ±9 % of the programmed output voltage as well as fault conditions. The LT8620 is available in small 3 mm ? 5 mm QFN package with exposed pads for low thermal resistance.

An oscillator, with frequency set using a resistor on the RT pin, turns on the internal top power switch at the beginning of each clock cycle. Current in the inductor then increases until the top switch current comparator trips and turns off the top power switch. The peak inductor current at which the top switch turns off is controlled by the voltage on the internal VC node. The error amplifier servos the VC node by comparing the voltage on the VFB pin with an internal 0.97 V reference. When the load current increases it causes a reduction in the feedback voltage relative to the reference leading the error amplifier to raise the VC voltage until the average inductor current matches the new load current. When the top power switch turns off, the synchronous power switch turns on until the next clock cycle begins or inductor current falls to zero. If over-load conditions result in more than 3.8 A flowing through the bottom switch, the next clock cycle will be delayed until switch current returns to a safe level. If the EN/UV pin is low, the LT8620 is shut down and draws 1 ?A from the input. When the EN/UV pin is above 1 V, the switching regulator will become active.

To improve efficiency across all loads, supply current to internal circuitry can be sourced from the BIAS pin when biased at 3.3 V or above. Else, the internal circuitry will draw current from V_{IN}. The BIAS pin should be connected to V_{OUT} if the LT8620 output is programmed at 3.3 V or above.

Comparators monitoring the FB



65 V/2 A Buck regulator LT8620

pin voltage will pull the PG pin low if the output voltage varies more than ±9 % (typical) from the set point, or if a fault condition is present. The oscillator reduces the operating frequency when the voltage at the FB pin is low. This frequency foldback helps to control the inductor current when the output voltage is lower than the programmed value which

occurs during start-up or over-current conditions. When a clock is applied to the SYNC pin or the SYNC pin is held DC high, the frequency foldback is disabled and the switching frequency will slow down only during over-current conditions.

Application Example

An application requiring 1A output should use an inductor with an RMS rating of greater than 1 A and an I_{SAT} of greater than 1.3 A. During long duration over-load or short-circuit conditions, the inductor RMS routing requirement is greater to avoid overheating of the inductor. To keep the efficiency high, the series resistance (DCR) should be less than 0.04 Ω, and the core material should be intended for high frequency applications.

The LT8620 limits the peak switch current in order to protect the switches and the system from over-load faults. The top switch current limit (I_{LIM}) is at least 3.8 A at low duty cycles and decreases linearly to 2.8 A at DC = 0.8 V. The inductor value must then be sufficient to supply the desired maximum output current ($I_{OUT(MAX)}$), which is a function of the switch current limit (I_{LIM}) and the ripple current.

In order to achieve higher light load efficiency, more energy must be delivered to the output during the single small pulses in Burst Mode operation such that the LT8620 can stay in sleep mode longer between each pulse. This can be achieved by using a larger value inductor (i.e. 4.7 µH), and should be considered independent of switching frequency when choosing an inductor. For example, while a lower inductor value would typically be used for a high switching frequency application, if high light load efficiency is desired, a higher inductor value should be chosen.

Bypass the input circuit with a ceramic capacitor of X7R or X5R type placed as close as possible to the V_{IN} and PGND pins. Y5V types have poor performance over temperature and applied voltage, and should not be used. A 4.7 µF to 10 µF ceramic capacitor is adequate to bypass the LT8620 and will easily handle the ripple current. Larger input capacitance is required when a lower switching frequency is used. If the input power source has high impedance, or there is significant inductance due to long wires or cables, additional bulk capacitance may be necessary. This can be provided with a low performance electrolytic capacitor.

Step-down regulators draw current from the input supply in pulses with very fast rise and fall times. The input capacitor is required to reduce the resulting voltage ripple at the LT8620 and to force this very high frequency switching current into a tight local loop, minimizing EMI.

A 4.7 µF capacitor is capable of this task, but only if it is placed close to the LT8620. A second precaution regarding the ceramic input capacitor concerns the maximum input voltage rating. A ceramic input capacitor combined with trace or cable inductance forms a high quality (under damped) tank circuit. If the LT8620 circuit is plugged into a live supply, the input voltage can ring to twice its nominal value, possibly exceeding the regulator's voltage rating.

The output capacitor has two essential functions. Along with the inductor, it filters the square wave generated by the regulator to produce the DC output. In this role it determines the output ripple, thus low impedance at the switching frequency is important. The second function is to store energy in order to satisfy transient loads and stabilize the control loop. Ceramic capacitors (X5R or X7R types) have very low equivalent series resistance (ESR) and provide the best ripple performance.

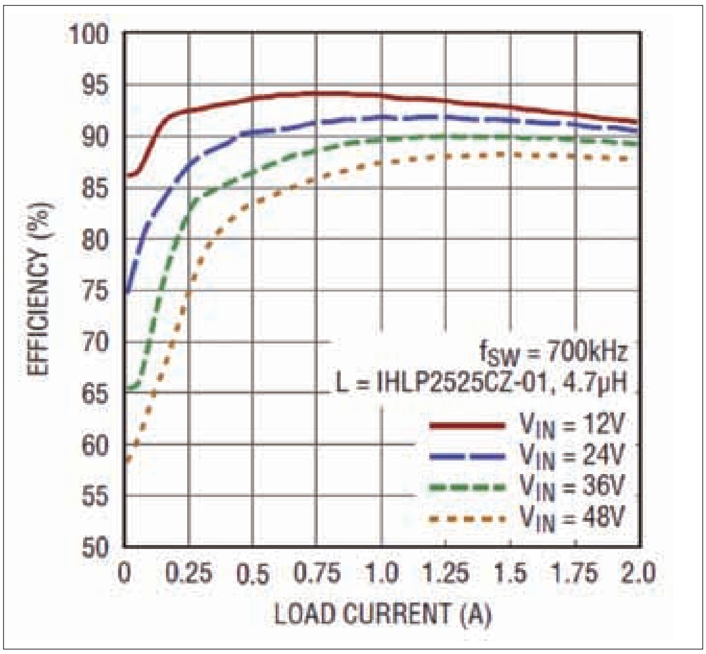
Transient performance can be improved with a higher value output capacitor and the addition of a feed-forward capacitor placed between V_{OUT} and FB. Increasing the output capacitance will also

decrease the output voltage ripple. A lower value of output capacitor can be used to save space and cost but transient performance will suffer and may cause loop instability.

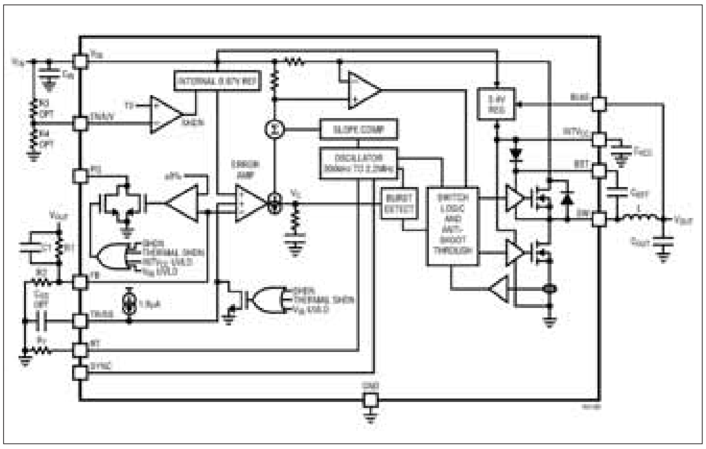
Ceramic capacitors are small, robust and have very low ESR. However, ceramic capacitors can cause problems due to their piezoelectric nature. When in Burst Mode operation, the LT8620's switching frequency depends on the load current, and at very light loads the device can excite the ceramic capacitor at audio frequencies, generating audible noise. Since the regulator operates at a lower current limit during Burst Mode operation, the noise is typically very quiet to a casual ear.

If this is unacceptable, a high performance tantalum or electrolytic capacitor should be used at the output. Low noise ceramic capacitors are also available.

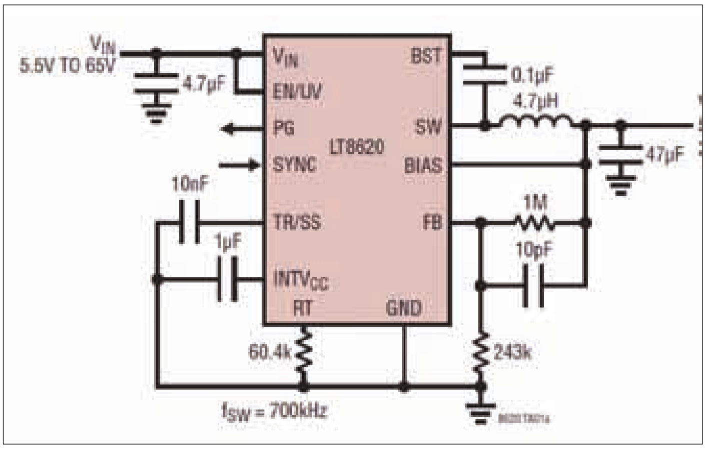
The LT8620 allows the user to program its output voltage ramp rate by means of the TR/SS pin. An



Efficiency at 5 V output and various input voltages



LT8620 block diagram



Typical truck application at 5 V/2 A output

internal 1.9 µA pulls up the TR/SS pin to INTVcc. Putting an external capacitor on TR/SS enables soft starting the output to prevent current surge on the input supply. During the soft-start ramp the output voltage will proportionally track the TR/SS pin voltage. For output tracking applications, TR/SS can be externally driven by another voltage source. From 0 V to 0.97 V, the TR/SS voltage will override the internal 0.97 V reference input to the error amplifier, thus regulating the FB pin voltage to that of TR/SS pin. When TR/SS is above 0.97V, tracking is disabled and the feedback voltage will regulate to the internal reference voltage. The TR/SS pin may be left floating if the function is not needed.

PCB Layout

For proper operation and minimum EMI, care must be taken during printed circuit board layout. Large, switched currents flow in the VIN pins, GND pins, and the input capacitor. The loop formed by the input capacitor should be as small as possible by placing the capacitor adjacent to the VIN and GND pins. When using a physically large input capacitor the resulting loop may become too large in which case using a small case/value capacitor placed close to the VIN and GND pins plus a larger capacitor further away is preferred. These components, along with the inductor and output capacitor, should be placed on the same side of the circuit board, and their connections should be made on that layer. The exposed pad on the bottom of the package must be soldered to ground so that the pad is connected to ground electrically and also acts as a heat sink thermally.

www.linear.com/product/LT8620

GaN – Moving Quickly into Entirely New Markets

Gallium Nitride (GaN) based power devices are rapidly being adopted due to their ability to operate at frequencies and switching speeds beyond the capability of Silicon power devices. With discrete GaN devices capable of switching at slew rates up to 70 V/ns, the system performance is greatly impacted by aspects outside the active power devices, such as high speed gate drivers and printed circuit board layout. In this article, the latest family of high frequency enhancement mode Gallium Nitride power transistors (eGaN FETs) is presented for use in multi megahertz buck converters. These devices were designed to address high-frequency hard-switching power applications at higher voltages. **Alex Lidow, Johan Strydom and David Reusch, Efficient Power Conversion (EPC), El Segundo, USA**

The introduction of a new family of high performance enhancement mode eGaN FETs offers the potential to switch at higher frequencies and efficiency than possible with traditional Si MOSFET technology. Combined with an improved switching figure of merit and low parasitic packaging, the new devices also have optimized device pin-out to minimize parasitic PCB layout inductance to fully utilize the device's capability. Example buck converters operating at 10 MHz show experimental peak efficiencies of over 89 %. Although the results are impressive, there is still a significant loss component due to the current silicon gate driver. To fully utilize the capability of the new high frequency, reduced size eGaN FETs, a focused improvement in the gate driver structure is required, which in turn will allow a further increase in efficiency and switching frequency capability.

Hard Switching FOM

The impact of the miller charge (Q_{GD}), which controls the voltage falling (t_f) and rising speed on the switching time is apparent and, for hard-switching applications, the use of Q_{GD} x $R_{DS(ON)}$ as a switching figure of merit (FOM) is common. For cases at lower voltages and higher currents, the current-dependent term (Q_{GS2}) cannot be neglected. Q_{GS2} is the portion of the gate source charge between the device threshold voltage (V_{TH}) to the gate plateau voltage (V_{PL}), which controls the current rising (t_r) and falling speed. These different gate charge portions are shown on the right side of Figure 1.

The idealized turn-on period, shown on the left side in Figure 1, begins with an increase of gate drive voltage; when the gate voltage reaches the threshold voltage, the current through the device will begin to rise, being driven by the gate current (I_G). During the drain current rising period, the transistor encounters both current and voltage in the device, resulting in switching loss. For the current rising period, the device parameter determining loss is Q_{GS2}. When the transistor current reaches the load current, the voltage across the device will begin to fall and more switching loss in the device will be incurred. For the voltage falling period, the device parameter determining loss is Q_{GD}. For the turn off switching losses, the same principles apply and minimizing the Q_{GD} and Q_{GS2} parameters will decrease switching losses incurred in a hard switching application. The overall switching loss is given by:

$$P_{SW} = \frac{V_{IN} \cdot I_{ON} \cdot (Q_{GD} + Q_{GS2})}{2 \cdot I_G} + \frac{V_{IN} \cdot I_{OFF} \cdot (Q_{GD} + Q_{GS2})}{2 \cdot I_G}$$

Over the years, a number of different figures of merit (FOMs) have been proposed to simply reflect the in circuit performance capability of a given device technology in different applications. The above idealized hard-switching power equations forms the basis of the hard-switching FOM (FOM_{HS}) or Q_{SW} x $R_{DS(ON)}$ = (Q_{GD} + Q_{GS2}) x $R_{DS(ON)}$ where Q_{SW} is the total switching gate charge during the

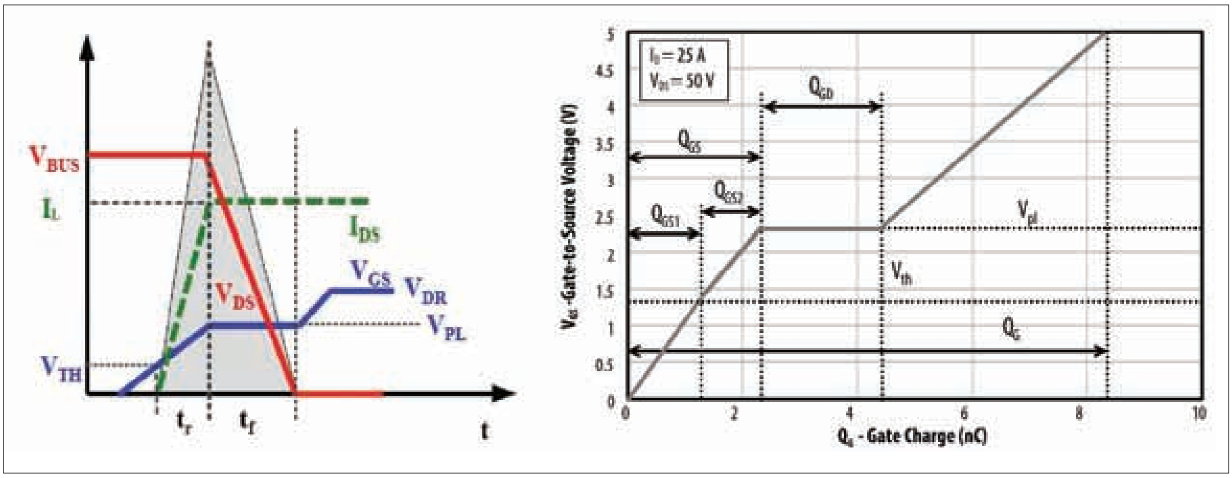


Figure 1: Idealized switching waveform used for calculating switching loss (left) and related FET charge diagram (right)

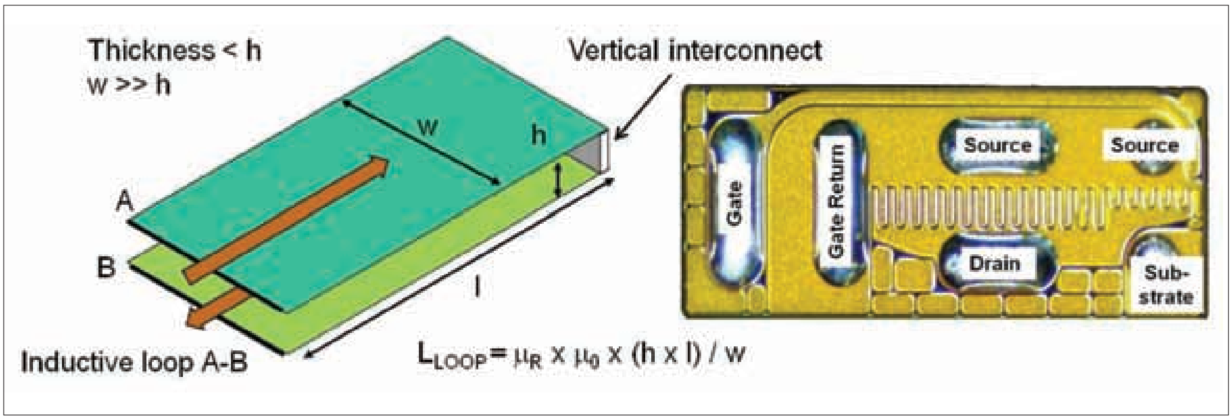


Figure 2: Optimum high frequency loop layout (left) and eGaN FET package showing pin-out (right)

hard switching interval.

These idealized switching waveforms rarely translate directly into actual in circuit performance results, as device and layout parasitics can significantly increase or even dominate switching losses. For a buck converter there are two major parasitic inductances that have a significant impact on converter performance: The common source inductance (L_S) is the source inductance shared by the drain-to-source power current path and gate driver loop; and the high frequency power loop (L_{LOOP}) is the power commutation loop and comprised of the parasitic inductance from the positive terminal of the input capacitance, through the top device, synchronous rectifier, ground loop, and back through the input capacitor. The common source inductance has been shown to be critical to performance because it directly impacts the switching speed of the devices.

The high frequency loop inductance, while not as penalizing to switching speeds as common source inductance, still negatively impacts switching performance. Another major drawback of high frequency loop inductance is the drain to source voltage spike induced during the switching transition, shown on the right in Figure 1. This voltage spike reduces maximum usable device voltage and increases switching loss. To enable the high switching speed available from the low FOM of GaN devices, low parasitic packaging and PCB layout, and separation of the gate and power loops to minimize common source inductance are required.

On the packaging level, this requires a low inductance package, such as a ball grid array (BGA) or other similar wafer level chip scale package (WLCSP). Furthermore, the common source inductance, being most critical parasitic, can be all but eliminated through the addition of a separate source terminal solely dedicated as a gate signal return path (gate return). To reduce power loop and gate loop reduction on a packaging level, the resultant board layout should be optimized. This is best achieved through generating large parallel conductors, where the loop current is flowing in opposite directions as shown in the left of Figure 2.

The current opposition results in magnetic flux cancellation outside the inductive loop, while minimizing the loop length and vertical interconnect height can reduce the magnetic energy storage inside the loop. Lastly, the conductor width should be maximized to minimize the inductance per unit length. To support this optimized layout structure on a packaging level, the device terminals should be designed to be wide and laid-out perpendicular to the power loop current flow direction. The resultant EPC8000 series eGaN FET package is shown on the right of Figure 2.

To push the switching frequency higher requires lower charge devices, which in turn result in higher on-resistance, suitable for lower power per phase operation. An example of such a reduced charge EPC8004 device is shown on the left in Figure 3 and is compared to the smallest existing same voltage (40 V) rated device, the EPC2014 and shows about a seven times reduction in gate charge.

Another important aspect to consider is dv/dt immunity. An important metric for dv/dt immunity is the Miller ratio, which is an indicator of how susceptible gates are to turning back on at high dv/dt. For the EPC8000 series, the Miller ratio (Q_{GD}/Q_{GS1}) at half rated voltage has been reduced to

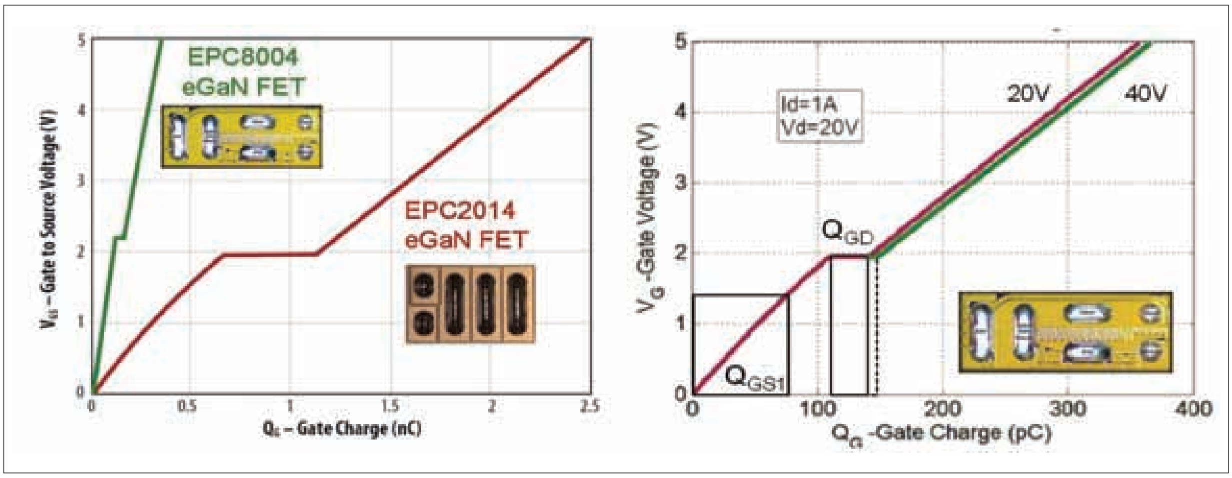


Figure 3: Gate charge diagrams, showing relative size of an EPC8004 device and existing EPC2014 device (left) and the EPC8004 device's inherent dv/dt immunity resulting from miller charge ratio (Q_{GD}/Q_{GS1} < 1) (right)

below 0.4, well below the theoretical requirement of one. The EPC8004 charge diagram, showing the Q_{GS1} and Q_{GD} intervals are shown on the right in Figure 3. It is important to note that the Miller ratio should remain below one, even up to full rated voltage, if dv/dt induced turn-on is to be avoided.

New Applications

GaN technology is enabling entirely new applications. In this article, we explore GaN penetration in four of these new applications, envelope tracking, wireless power transfer, LiDAR, and satellites. We also discuss GaN's penetration in the original target market, DC/DC conversion. The overall conclusion is that GaN is creating markets that are as large as the markets where they are displacing their Silicon ancestors.

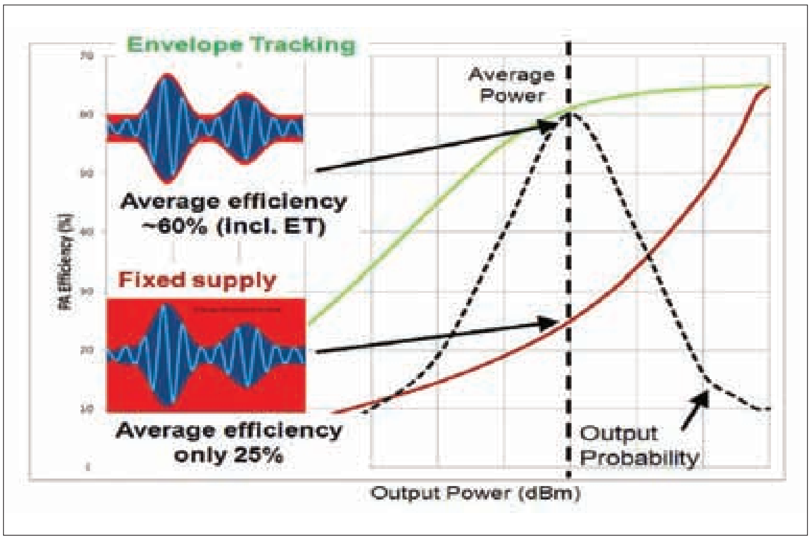
Envelope Tracking: The concept of envelope tracking for radio frequency amplifiers is not new. But the ever-increasing need for better base station efficiency and output power, as well as the need for improving RF power amplifier efficiency, is driving intense research and development in envelope tracking. RF power amplifiers are used to transmit all of our voice and data through satellites, base stations, and cell phones. Conventional RF power amplifiers operate at a fixed power level delivering maximum power whether or not the transmitter needs it. When envelope tracking is deployed in a RF power amplifier, the amplifier does not operate at a fixed power level, but precisely fits the power delivered to the amplifier's signal modulation needs. This is illustrated in Figure 4. Figure 5 shows a prototype board for envelope tracking applications.

For many years designers have tried to make envelope tracking work using expensive LDMOS transistors without general success. However, the power modulation required is enabled by enhancement-mode GaN transistors that can operate at the high voltages and switching speeds needed for efficient envelope tracking, which are just beyond the reach of Silicon.

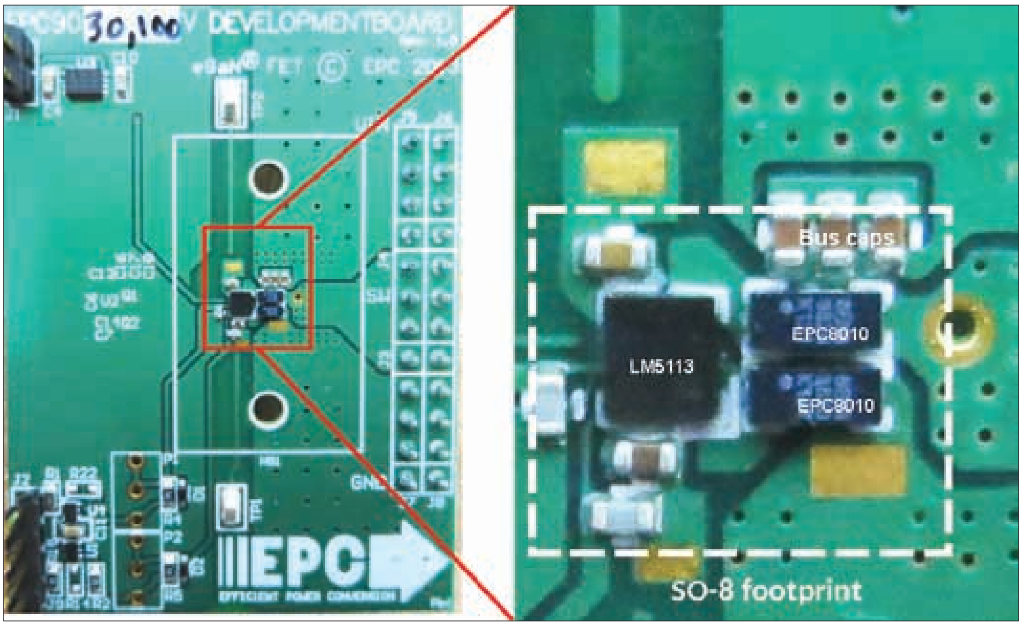
RF power amplifiers for 4G LTE technology have higher power requirements than previous generations and are the biggest beneficiary of envelope tracking. Today 4G LTE technology is just nine percent of the global wireless platform, but will eventually supersede earlier 3G networks in the world of data transmission. Envelope tracking can double the energy efficiency of RF power amplifiers for the 4G network with even greater gains probable for 5G.

Wireless Power: Wireless power applications are gaining popularity in many commodity products such as mobile phone chargers. Most of the wireless power solutions to date have focused on tight coupling with induction coil solutions operating at frequencies around 200 kHz. This is the Qi standard and its major drawbacks are conversion efficiency and its requirement for exact placement of the devices so that the transmit and receive coils are aligned.

Industry leaders including Qualcomm, Intel, Broadcom, Samsung, Delphi, and Witricity, have established a consortium (A4WP) for the development and commercialization of a recently selected high-frequency standard (6.78 MHz) for wireless power transmission (Highly Resonant Power Transfer). The fast switching capability of GaN transistors is ideal for highly resonant power transfer applications, particularly when high



ABOVE Figure 4: **Schematic of fixed and envelope tracking power profile in a RF Power amplifier**



LEFT Figure 5: **Prototype board for envelope tracking applications**

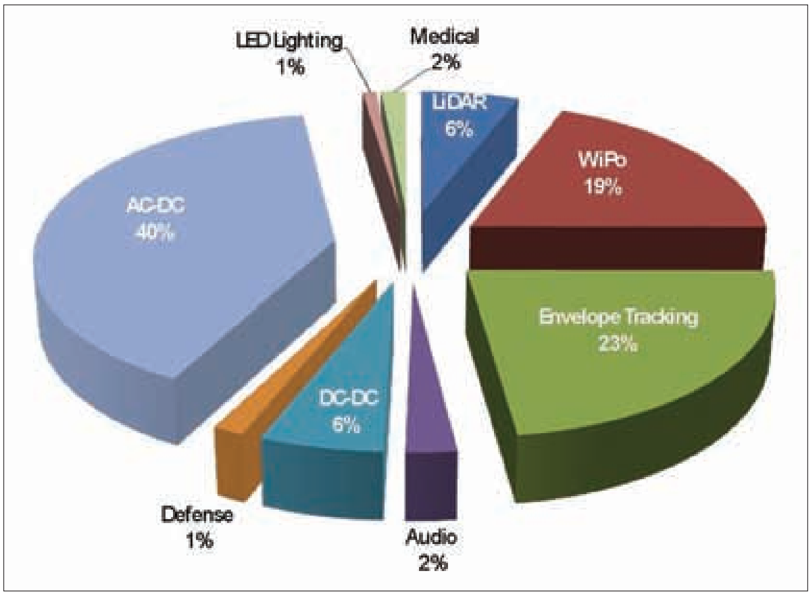


Figure 6: **EPC's projected revenue by application in 2018**

transfer efficiency and robust foreign object detection is desired.

Initial applications for wireless power transfer include cell phones, game controllers, laptop computers, tablets, and even electric vehicles that re-charge without being plugged in or having actual physical contact, merely proximity within a specified range is all that is required. The global wirelesses power transfer market CAGR is estimated at 55.5 %, and is forecasted to be $15.1 billion by 2020. Demand for automotive wireless charging alone is expected to triple in the next eight years.

LiDAR: Light Detection and Ranging uses pulsed lasers to rapidly create a three dimensional image or map of a surrounding area. One of the earliest adopters of this technology is the Google Maps "driverless" cars. Today's enhancement-mode GaN transistors' higher frequency capability results in LiDAR systems with superior spacial resolution, faster response time, and greater accuracy. These device characteristics enable new and broader applications such as real-time motion detection for video gaming, computers that respond to hand gestures as opposed to touch screens, and fully autonomous vehicles.

Rad Hard: Power converters used in harsh environments, such as space, high-altitude flight, or high-reliability military applications must be resistant to damage or malfunctions caused by radiation. Most electronic components require specialized design or manufacturing processes to reduce their susceptibility to radiation damage. For this reason, radiation-hardened devices tend to lag behind the most recent technology developments. Silicon-based power MOSFETs are no exception, and enhancement-mode GaN transistors have been shown to perform 40 times better electrically while being able to withstand 10 times the radiation. In addition, since commercial grade GaN power transistors are intrinsically radiation-hardened, they open the door to major cost savings in communications and research satellites. It is anticipated that the overall $ 200 billion global space market in 2023 will drive a greater than $100 million Rad Hard transistor market that will be dominated by GaN transistors.

Datacom DC/DC: The hunger for more efficiency continues to be a driving factor in most electronics – especially in applications such as server farms and centralized telecommunications centers. When compared with MOSFETs, GaN transistors are significantly more efficient. The lower power losses translate into products with higher output, improved power density, and increased efficiency. This translates into lower energy consumption and reduced electric bills.

More to Come

We expect GaN devices to re-enact the famous Moore's Law in the coming years, expanding beyond discrete transistors into a variety of integrated circuits with high performance, low cost, and very high value. This drives a "virtuous cycle" where each subsequent generation has increasingly higher performance and lower cost, thus enabling even more new, unforeseen applications.

GaN is facing a period of very rapid growth. This growth is coming from both the replacement of lower performing (and soon to be higher relative cost) Silicon devices and from emerging applications that are enabled by GaN's performance. Figure 6 shows EPC's forecasted 2018 revenue breakout for its eGaN FET product line. Emerging applications, LiDAR, envelope tracking, and wireless power transfer, represent 48% of these projected revenues – applications that are in their infancy today, but are exploding on the market.

Literature

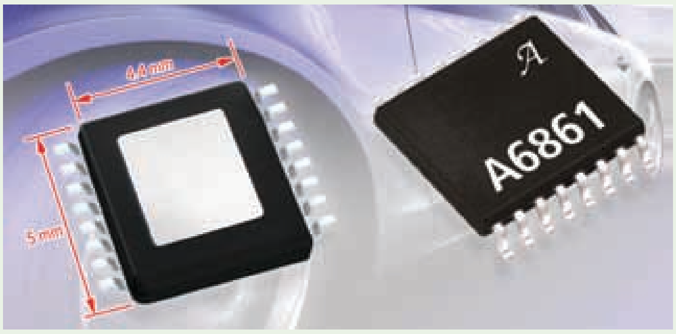
'Multi Megahertz Buck Converters using eGaN® FETs for Envelope Tracking' Johan Strydom and David Reusch, Efficient Power Conversion Corporation (EPC), PP44 PCIM Europe 2014

N-channel E-Mode power MOSFET

Advanced Power Electronics Corp. (USA) has launched a new cost-effective N-channel enhancement-mode power MOSFET offering a fast switching performance and ultra low on-resistance for low voltage applications such as DC/DC converters and load switching. The AP100T03GP-HF-3 MOSFET comes in a TO-220 through-hole package which is popular for commercial and industrial surface-mount applications requiring a small PCB footprint or an attached heatsink. The new power MOSFET benefits from simple drive requirements and offers a fast switching performance, low on-resistance of 2.1mΩ, a drain-source breakdown voltage of 30 V, and a continuous drain current of 215 A. The component is halogen-free and fully RoHS-compliant.

www.a-powerusa.com/docs/AP100T03GP-3.pdf

Automotive 3-phase MOSFET Driver IC



The new A6861 from Allegro MicroSystems Europe is a 3-phase N-channel power MOSFET driver IC with built-in isolation designed to meet Automotive Safety Integrity Level (ASIL) requirements in applications such as electronic power steering, electric braking, and three-phase relay drivers. The new A?-SIL™ device is designed to replace mechanical relays and discrete driver circuits in safety-critical automotive applications where motor isolation is an essential requirement. The A6861 has three independent floating gate drive outputs to maintain the power MOSFETs in the "on" or "off" state over the full supply range in the presence of high phase-voltage slew rates. With the addition of a few external components, it can also isolate the load when high load currents are present. An integrated charge pump regulator provides the above battery supply voltage necessary to maintain the power MOSFETs in the "on" state continuously when the phase voltage is equal to the battery voltage. The charge pump will maintain sufficient gate drive (above 7.5 V) for battery voltages down to 4.5 V with 100 kΩ gate-source resistors. The three gate drives can be independently controlled. In typical applications the MOSFETs will be switched on within 8 µs and will switch off within 1 µs. An under-voltage monitor checks that the pumped supply voltage is high enough to ensure that the MOSFETs are maintained in a safe conducting state.

www.allegromicro.com

Polypropylene Film Capacitors for SMPS

AVX has released the FM Series medium power film capacitors featuring non-inductively wound with dry, metallized polypropylene film dielectric and encapsulated in a flame retardant plastic case sealed with self-extinguishing, thermosetting epoxy resin and RoHS-compliant double metallized polyester film electrodes in series construction. Rated for capacitance values spanning 0.01 µF to 0.47 µF, voltages spanning 250 V to 2000 V, and operating temperatures spanning -40°C to +105°C, the new FM Series capacitors are designed for high frequency and high pulse rise-time circuits, high voltage power supplies, switch mode power supplies (SMPS), power converters, snubbers, and electronic lighting ballasts, such as compact florescent lamps and LEDs. Unlike aluminum electrolytic capacitors, FM Series film capacitors do not have a catastrophic failure mode, they experience a parametric loss of capacitance of approximately 2 % from their initial value, eliminating the risk of short circuit and enabling continued functionality.

www.avx.com/docs/Catalogs/FM%20_4.pdf

Flatpack Capacitors Handle High Vibration

Cornell Dubilier Electronics (CDE) has expanded its line of MLS Flatpack aluminum electrolytic capacitors to include a high vibration package, type HVMLS and a high reliability burn-in option, type HRMLS. Applications are mainly for bulk storage, where relatively expensively wet tantalum capacitors had previously been the only type suited. The MLS family of capacitors are packaged in flat, stainless steel cans, one-half inch in height with a near hermetic, precision welded construction. Their flat form factor allows them to be fit into tight spots, easily cooled, and easily ganged for compact, high bulk storage. The high vibration HVMLS version is further enhanced with ruggedized internal terminations and compressed can edges that keep the internal winding secure when tested up to 50 g of vibration.

www.cde.com

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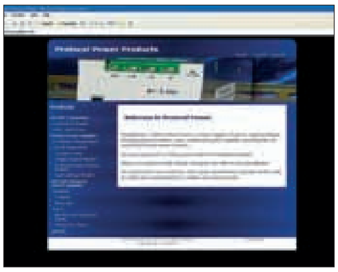

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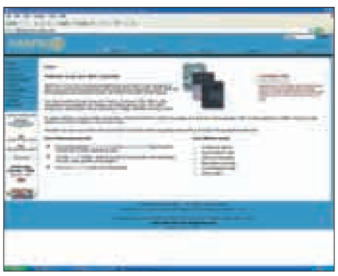

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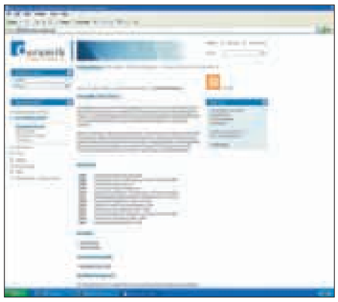

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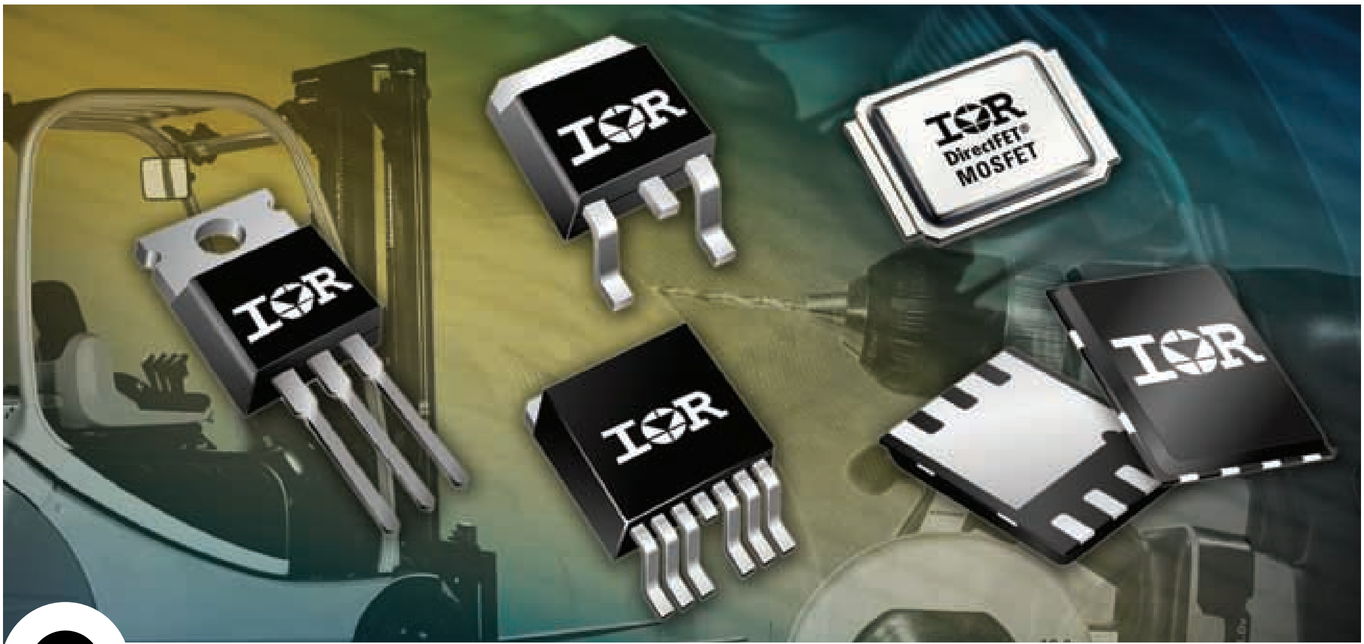

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	30	100	1.1	58	IRFH8303TRPbF
	30	100	1.3	50	IRFH8307TRPbF
	40	100	1.4	134	IRFH7004TRPbF
	40	85	2.4	92	IRFH7440TRPbF
	40	85	3.3	65	IRFH7446TRPbF
DirectFET Med.Can	30	192	1.3	51	IRF8301MTRPbF
	40	90	1.4	141	IRF7946TRPbF
	60	114	3.6	120	IRF7580MTRPBF
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	40	120	2.8	90	IRFS7440TRLPbF
	60	120	5.34	86	IRFS7540TRLPbF
D^2-Pak 7pin	40	195	1.5	150	IRFS7437TRL7PP
	60	240	1.4	236	IRFS7530-7PP
D-Pak	40	90	2.5	89	IRFR7440TRPbF
	60	90	4	86	IRFR7540TRPbF
TO-220AB	40	195	1.3	300	IRFB7430PbF
	40	195	1.6	216	IRFB7434PbF
	40	195	2	150	IRFB7437PbF
	40	120	2.5	90	IRFB7440PbF
	40	118	3.3	62	IRFB7446PbF
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