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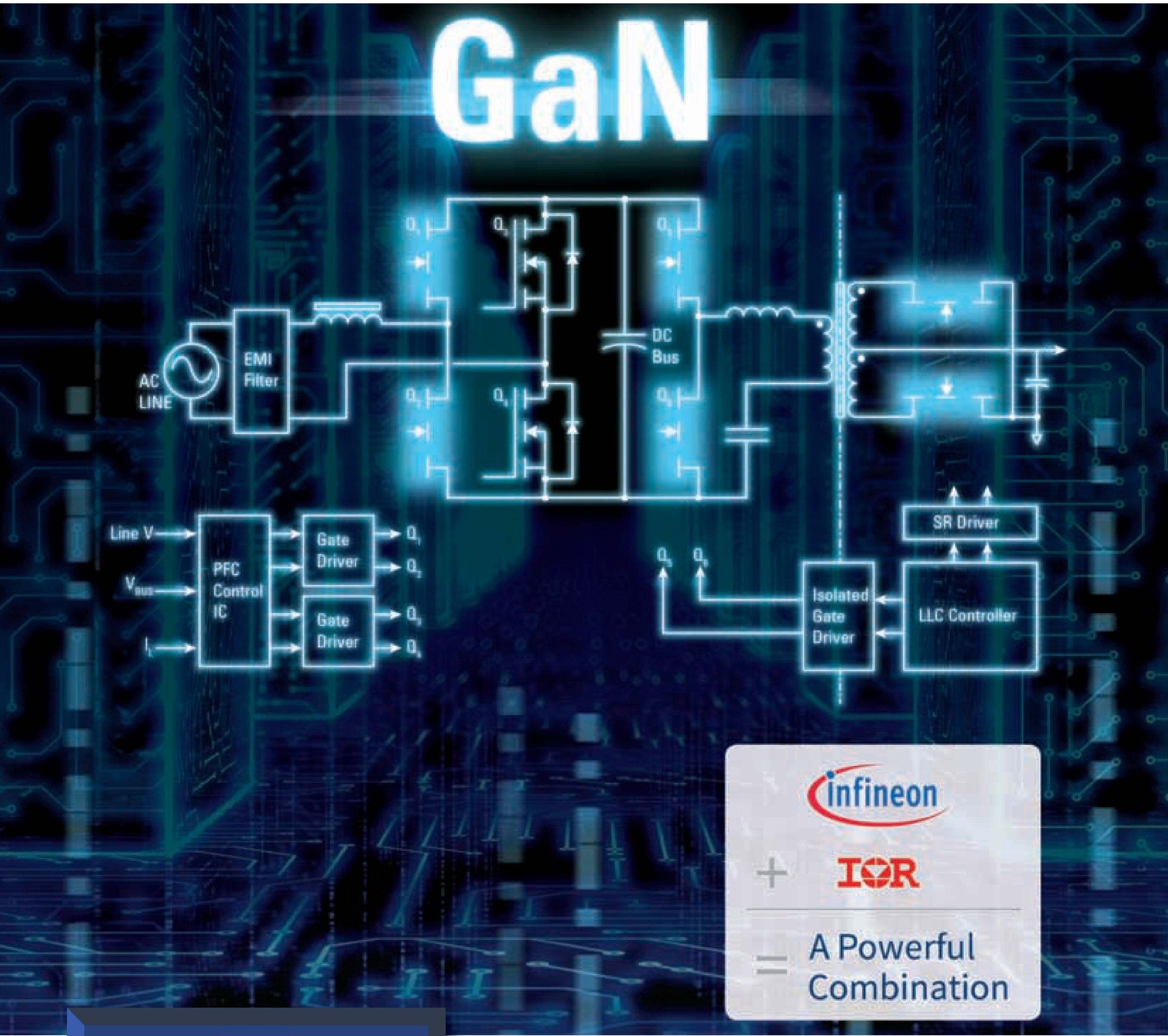
POWER SEMICONDUCTORS

How 600 V GaN Transistors Improve Power Supply Efficiency and Density



THE EUROPEAN JOURNAL FOR POWER ELECTRONICS AND TECHNOLOGY

Also inside this issue

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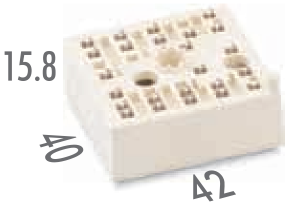
Innovating Energy Technology

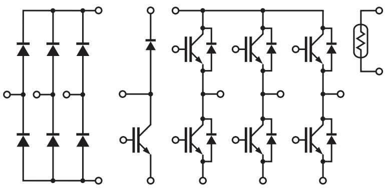
V-Series IGBTs

- Trench-FS IGBT
- High thermal cycling capability
- Low spike voltage & oscillation free
- Excellent turn-on dI_C/dt control by R_G

Fuji Electric's MiniSKiiP®

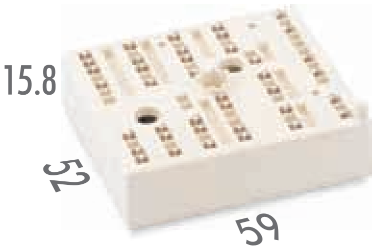
MiniSKiiP® 1

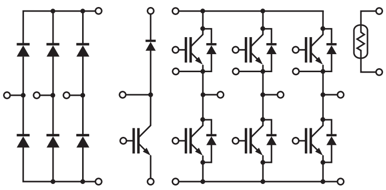




I_C	1200V
8A	●
15A	●

MiniSKiiP® 2

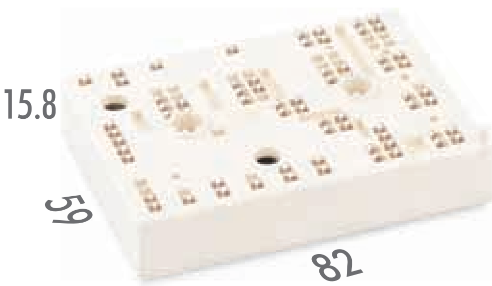


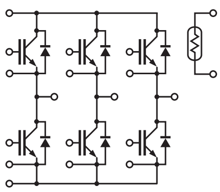


I_C	1200V
25A	●
35A	●

Available also with larger rectifier diodes

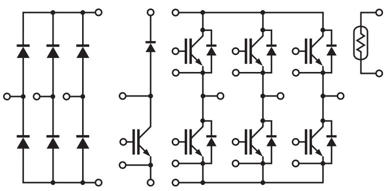
MiniSKiiP® 3





I_C	1200V
100A	●
150A	●

Under development



I_C	1200V
50A	●
75A	●
100A	●

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The Race is Opened

During the last years new power semiconductor technologies such as SiC-FETs (MOSFETs and JFETs) and lateral GaN-HEMTs evolved. Whereas the SiC devices convince with great performance but still suffer from high wafer costs and wafer diameter limitations, GaN-HEMTs can be manufactured on large and cheap Si-wafers – but still have deficiencies with respect to ruggedness and require significant nominal voltage derating. In parallel to this development the traditional Si-based technologies like IGBT and super junction MOSFETs like CoolMOS have improved continuously. Especially in the 600 V to 1200 V blocking range this result in very competitive situation, no clear long term winner can be identified today – according to Infineon the race will be decided differently for different applications.

Infineon's CoolMOS family already achieves the value of 1 ohm mm? by reducing cell pitch and compensation accuracy. Modern SiC switch concepts promise a factor 5 lower on resistance, but this is easily eaten up by the higher SiC area costs in 650 V. In parallel also the energy stored in the output capacitance of the new CoolMOS devices was reduced by more than a factor 2 now being pretty close to the SiC and GaN values, i.e. for hard switching applications like classical power facor correction there is very little benefit left for WBG switches. However there is stagnation with respect to charge stored in the output capacitance, the key parameter for so-called resonant applications or hard switching bridges. Here both SiC and GaN will clearly outperform the Silicon MOS solutions and get justification for a price premium. Regarding IGBTs - by tailoring the local plasma density in sophisticated trench structures the power density especially in the 650 V range was also significantly improved in the last years, coming to new and improved saturation vs. switching loss trade-offs. In many cases this approach is only hampered by the high resulting saturation current and the related low short circuit robustness, what is a restriction in various applications. Also another drawback of the IGBT – the missing integrated free-wheeling diode – is meanwhile addressed and quite encouraging results are available for the so called reverse-conducting IGBT. With respect to manufacturing cost, the IGBT is clearly superior to all other power switch technologies and has the lowest temperature dependence of conduction losses. But even with all the recent performance improvements, the WBG switches are providing only 1/10th of the switching losses, if the application allows high dV/dt and the assembly setup is low inductive.

SiC diodes meanwhile have more than a decade commercial history and are a fixed part of high end power supplies, but SiC switches are still in an early stage of market penetration. Reasons are, according to Infineon, challenges concerning gate oxide quality and channel mobility which do not allow to make use of the full potential of the material. On the other hand, the average annual

cost decrease of SiC base material was around 12 percent over the last decade, allowing the SiC switches becoming more and more competitive. Especially in 1200 V applications, where there are no super junction MOSFETs available, higher switching frequencies provide system advantages through higher power densities. Efficiency is critical and a low loss body diode is required for application in solar converters or UPS.

GaN HEMT devices are completely different from the traditional FETs as they are lateral, have very low gate charge, contain no body diode and show destructive dielectric breakdown instead of avalanche. The very low on-resitance of those devices allows high power densities, but on the other hand this is hampered by the low thermal capacitance and thermal conductivity of the GaN-on-Si structure. However extremely low switching losses due to the high carrier mobility motivate even the development of new circuit designs for e.g. power supplies constructed around the specific set of properties of the GaN switches – especially as there is hope, that in the future such GaN switches will be even cheaper than CoolMOS in the 650 V range.

Obviously the latter motivated Infineon to invest in GaN through the acquisition of International Rectifier, the recognized leader in this and other power semiconductor technologies. "The acquisition of International Rectifier is an important step for Infineon to foster our position as a global market leader in power semiconductors. We are sure that International Rectifier and its employees will make a great contribution to a joint successful future. Together both companies make a powerful combination. The acquisition helps us to accelerate our strategic approach 'from product thinking to system understanding", commented Dr. Reinhard Ploss, CEO of Infineon. He will integrate the acquired company within Infineon's Automotive and Power Management business segments and switch most of IR's production to its better performing 300-mm Silicon production lines.

More details on that deal and corresponding technologies can be read within this issue. Enjoy it!

Achim Scharf
PEE Editor

In Search for New Market Opportunities

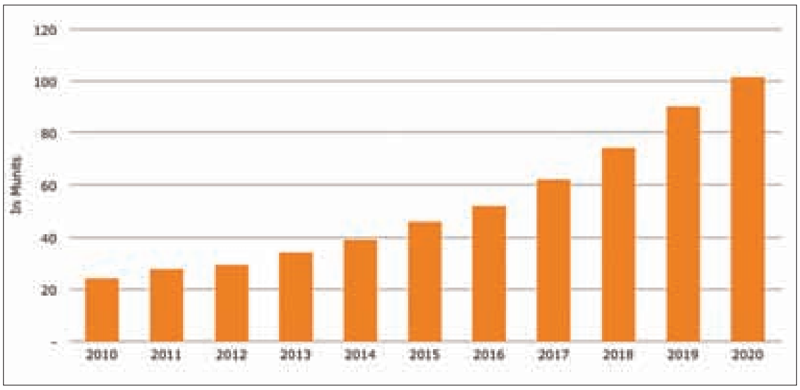
Wide band gap technologies are almost ready to be used by power electronics integrators. The question is now - how? Industry players have identified many module packaging challenges. Market researcher Yole Développement has analyzed their insights, and is now presenting an overview of the issues.

The power electronics industry has been focusing its research and development on WBG technologies. Under this strategy, Silicon Carbide (SiC) and Gallium Nitride (GaN) have proved to be powerful solutions. They are now ready to be implemented in numerous power electronics applications. Most companies today choose SiC technologies for high temperature and high voltage applications. Yole confirms that SiC is propagating across all industrial segments. Contagion has begun. In parallel companies are developing GaN solutions for medium-voltage applications, especially GaN HEMT transistors.

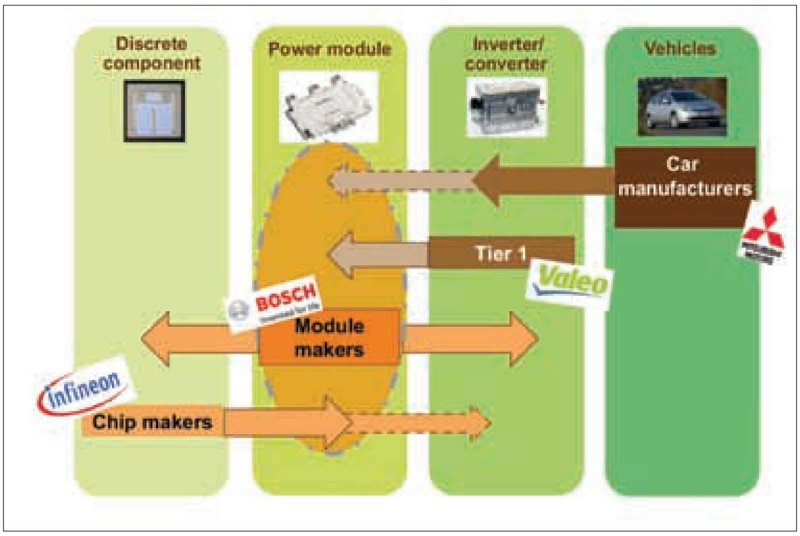
Missing device integration

However, Yole's analysts have identified a potential bottleneck for WBG technologies' adoption - device integration, especially at the power module packaging level. "WBG market shares are not directly linked to WBG component availability", highlights Yole's Pierric Gueguen, Business Unit Manager, Power Electronics. Instead they depend on when integrators will get benefits from such solutions. New WBG-based solutions induce research expenses at the power module packaging level. Such costs must be compensated for by added value at the system, compare to existing silicon solutions. "Integrators could ensure such added value by integrating WBG devices with an increased operating frequency and temperature", explains Gueguen.

Yole's power electronics activities follow the industry all along the supply chain - from basic components to power modules. Today, Yole's team is mixing a "bottom-up" methodology, taking into account business opportunities of innovative technologies and a "top-down" analysis, more focused on the market needs from the applications side. Before Yole, Gueguen oversaw power electronic converters' and WBG devices' integration into electric vehicles. With that knowledge he announced that in 2015 Yole will concentrate its power electronics analysis on device integration. "The expected rebound from electric and hybrid electric vehicle applications and the emergence of smart-grid projects did not occur in 2013," he stated. "Indeed, the car market was still depressed and the industry segment not strong enough to sustain high volumes." And what about Chinese players? Over the last few years, their leadership has been confirmed among their local markets. These companies are now looking for international business opportunities. Such a strategy could reinforce their positioning and strongly modify the supply chain within the still growing power semiconductor market.



Overall inverter market development including EV/HEV, buses, drives, UPS and wind



EV/HEV market will reshape business models and the power electronics supply chain

Dependent on automotive applications

"The $65 billion inverter market by 2020 will be driven by multiple applications. The largest markets in revenues by 2020 will be represented by motor drives, UPS, and PV", Gueguen forecasts. "The strongest market growth will be featured by EV/HEV, with 18 percent CAGR between 2013/2020 and wind and UPS markets remaining almost flat", he adds. "The inverter supply chain is changing to align with new customers' requirements. This was first learned in the PV industry when the first SiC inverters were introduced several years ago by SMA and REFUsol (now AEI), since then the highest customer priority has changed from high efficiency to low cost."

The Electric Vehicle / Hybrid Electric Vehicle (EV/HEV) supply chain is evolving and power electronic module manufacturing attracts more and more companies, car makers, modules suppliers, chip makers to develop their own expertise. According to automotive experts, electric and hybrid vehicles have been announced as a huge market over the last few years. However, in 2013, only 100,000 pure electric vehicles were sold, and only 2 million EV/HEV cars in total. Battery cost reduction, power density increase, or charging infrastructure development are pushing the EV/HEV market forward and cause cost reduction. "Due to the market growth and the progressing technologies, the price difference between EV/HEV and gas powered vehicles will progressively shrink and accelerate the development of this market", adds Gueguen.

But the automotive industry know-how has historically been built around the combustion engine. The transition to EV/HEV technology is slow and based on the know-how transformation from combustion engine to power electronics including inverters and power modules, the key EV/HEV vehicles ingredients. Nevertheless, EV/HEV players are all converging on the power module manufacturing. For example, beginning of 2014, Mitsubishi Electric announced the development of EV motor drive system with built-in Silicon Carbide inverter. Inverter/converter makers such as Valeo, follow the same strategy and develop a specific know-how dedicated to power module technologies. In parallel, Bosch, initially supplier of power modules, expands its expertise towards both directions, components and inverters/converters. In January 2014, the company confirms its commitment to EV market with Chrysler, by supplying inverters.

www.yole.fr

Different Electric Vehicles Pioneer Best Technology First

To benchmark new technology for electric vehicles it is vital to look at all of the off-road, on-road, water and airborne e-vehicles analysed in the IDTechEx report, "Electric Vehicle Forecasts, Trends and Opportunities 2015-2025".

For example, electric cars will have at least six types of energy harvesting variously converting ultra violet, infrared, visible light, vibration, vertical, lateral and forward movement into electricity but also heat differences. However, none of these first appear in cars. Combined energy harvesting is also seen elsewhere first - from military to marine vehicles. Energy harvesting shock absorbers (Levant Power) are trialled on buses, not cars because they are most easily made viable on large vehicles first. Proponents expect to address cars about five years after buses adopt them, including taking some of the "free" electricity and using it for active suspension. Thermoelectric harvesting (AIST, Komatsu KELK) will be more practicable on buses, military and other large vehicles before cars. Structural electronics - where the bodywork is intelligent and power storing - was first seen in aircraft then cars.

In-wheel traction motors are in production buses in the Netherlands, China and Japan. Lower cost, more rugged asynchronous motors are favoured in large then smaller vehicles. Following this, the Proton hybrid car is being launched in 2015 with in-wheel asynchronous motors. Jet engines have proved viable on some buses when used as range extenders. Rotary combustion engines, first seen in e-aircraft, will appear in Proton cars as range extenders in 2015.

In 2014, the first series production of inverters with the more-efficient SiC power components (Sumitomo Electric, Panasonic) was for large vehicles. They run cooler so the weight, cost and bulk of water cooling is not needed and electricity is also saved. Voltages are rising. On buses we see up to 700 V systems using high-voltage, faster motors to save on copper and transfer power more efficiently. "Large electric vehicles usually adopt new technology first so they are a bellwether for the future of cars and two wheelers", said Peter Harrop, Chairman IDTechEx.

Launches of fuel cell cars are reportedly planned by up to six carmakers from 2015. Toyota has been the first to declare its hand with full details of its contribution the Mirai. People listen to Toyota because it is way ahead as leader in EVs overall with sales about four times those of number two according to analysts IDTechEx. It was right to say that affordable pure-electric cars using batteries were not ready for prime time and right to persevere with hybrids. It knows about pure electric vehicles: it is global leader in pure electric forklifts. Fuel cell rollout projects across the world are actually extremely cautious and modest. For example, the European HyFive program involves Toyota, BMW, Daimler, Honda and Hyundai. It only aims to get 110 fuel cell vehicles on the road by contributing $45 million.

Indeed, IDTechEx puts fuel cell cars at only 1 percent of all hybrid and pure electric cars sold worldwide in 2024. "Fuel cells will not be competitive with conventional engines in up-front cost for at least 15 years. Indeed, they need very expensive new hydrogen fuelling infrastructure in addition. The Germans may achieve that and the Californians are sprinkling 100 across the state by 2017 but that still means frequent diversions into further grid-locked roads to find the stuff. Fuel cells could eventually make sense for fleets such as forklifts and buses because providing their hydrogen refue?ling is trivial, given their fixed routes. Indeed, fuel cells are in about 8000 forklifts in the USA where hydrogen is cheaper. Reduced cost of ownership and no local pollution could become market drivers in closed systems", commented Franco Gonzalez, EV analyst at IDTechEx. "Meanwhile, the year is approaching when affordable battery cars arrive with the same lack of pollution at point of use, the same 300 miles range as fuel cells but acceptable resale price due to being simpler and lasting longer. In 2020, or not long after, that could provide lift-off in sales way beyond fuel cell cars. Indeed, fuel cell cars perpetuate the bad practice of putting platinum in a consumer product and they still need a supercapacitor or battery to do the heavy lifting. For example, the Toyota Mirai launched in 2015 has a 1.5kWh NiMH battery".

"So far, fuel cells are usually only range extenders for hybrids though one day they may manage all load variations. Even then they will need separate devices to accept the energy harvesting from braking, shock absorbers and photovoltaics", Gonzalez added. Thus IDTechEx would not be surprised to find Toyota launching hybrid cars with next-generation fuel extenders that are cheaper to buy and to own than fuel cells and easier to refuel. The question may then become whether to keep the exceptionally high subsidies for fuel cell cars when zero pollution at point of use becomes viable with arguably greener pure-electric battery or supercap-battery cars that need less investment. Indeed, electricity to charge the competing pure electric cars is increasingly green with greener grid power and increased use of local solar, including over the car itself, whereas affordable and easily accessed green hydrogen remains elusive.

www.idtechex.com/ev

SMBus 3.0 Specification Improves Power Management

The System Management Interface Forum (SMIF Inc.) has announced the latest version of its System Management Bus (SMBus) specification. Version 3.0 is backwards compatible and incorporates a number of major revisions to ease implementation for users of the protocol, significantly broaden performance capabilities to ensure compatibility with the latest topologies and harmonize the specification with the I?C and Power Management Bus (PMBus™) specifications.

The SMBus is a two-wire interface through which system component chips and devices can communicate with each other and with the rest of the system. SMBus is designed to provide a control bus for system and power management related tasks and may be used instead of individual control lines to pass messages to and from devices. In addition to reducing pin counts and supporting a flexible and expandable environment, SMBus delivers a useful range of functionality such as saving states from a suspended event and the reporting of errors.

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suspended event and the reporting of errors.

Recognizing the ability of the latest processors and custom logic to work at greater speeds, the 100 kHz bus frequency offered by SMBus 2.0 is complemented with two further speeds of 400 kHz and 1 MHz in the newly announced version 3.0. The addition of these increased speeds has in turn necessitated the adjustment and re-organization of high power electrical drive levels. A further update has seen the data hold time specification changed to match the I^2C specification. The decision to align this parameter recognizes that most devices on the market manage data hold time in accordance with I^2C.

Version 3.0 also includes the removal of a specification for minimum immunity to noise on the clock and data lines as the SMIF Working Group found that no supplier of SMBus devices or system OEM using SMBus ever tested against the parameter. Other changes include the re-use of defunct special bus addresses (formerly reserved for ACCESS Bus host and ACCESS Bus default address) for the zone read and write protocols that were introduced in revision 1.3 of the PMBus specification, an increase from 32 to 255 for the maximum number of bytes allowed in the write-block read process call, and the addition of protocols to read 32 and 64 bits of data in a single transaction.

Importantly, the changes to the SMBus specification will also support further improvements in the PMBus protocol standard. These improvements will be incorporated in the upcoming PMBus 1.3.1 specification.

http://pmbus.org/index.php

Securing Leading Position in Power Semiconductors

Infineon completed the acquisition of International Rectifier for $3 billion a few weeks ago. With this acquisition, the company have opened a new chapter in its history, outlined CEO Reinhard Ploss at the Annual General Meeting 2015 in February.

Since Infineon was founded 15 years ago, the company has divested itself of several lines of business. "That was not always easy, but they were the right steps to take. We have focused on markets in which we hold a leading position. In the last five years, we have shown that we can grow profitably over an entire economic cycle. We are now a very healthy business in a sound financial position", Ploss stated.

According to Ploss, Infineon and International Rectifier are an excellent match. The product portfolios of both companies complement each other perfectly. On the one hand, we are expanding our market position. On the other, this move adds technologies and products which have been on our roadmap for a long time. That is in line with our Product to System strategy. On top of that, the acquisition of International Rectifier extends our technology base with regard to compound semiconductors for power electronics such as Silicon Carbide and Gallium Nitride. In recent years, Infineon has already become a leading vendor of Silicon Carbide devices. International Rectifier is a globally recognized specialist for chips based on Gallium Nitride. Compound semiconductors open up whole new technical opportunities to increase energy efficiency. The acquisition will also deliver considerable cost benefits. On the one hand, the larger revenue base will improve the cost structure. On the other, production of 300-millimeter thin wafers faster can ramped up faster.

"Also we are strengthening our presence in the US. We are getting closer to Silicon Valley, the powerhouse for innovation especially in the connected world. We will also significantly reinforce our position in Asia, one of our most important growth markets. And finally, we will reach more and different customers thanks to the strength of International Rectifier in the distribution business. We expect International Rectifier to already make a positive contribution to Infineon's segment result this fiscal year. In fiscal year 2017 at the latest, International Rectifier's margin will be at least 15 percent, which is exactly in the target corridor we have set for Infineon", Ploss underlined. "Thus the acquisition of International Rectifier is an important part of our strategy as it strengthens us in terms of products, technology, regional presence and customer structure". More on the financial issues has already been published in PEE 1/15 on page 6.

"The larger revenue base together with International Rectifier will improve the cost structure on the one hand, on the other, production of 300-millimeter thin wafers faster can ramped up faster", Infineon's CEO Reinhard Ploss expects.

New Efficiency Standards for External Power Supplies

The global regulatory environment surrounding the legislation of external power supply efficiency and no-load power draw has rapidly evolved over the past decade since the California Energy Commission (CEC) implemented the first mandatory standard in 2004. With the publication of a new set of requirements by the United States Department of Energy (DOE) set to go into effect February 2016, the landscape is set to change again as regulators try to further reduce the amount of energy consumed by external power adapters.

Mandating higher average efficiencies in external power supplies has had a real impact on global power consumption. Original Equipment Manufacturers (OEMs) who design external power supplies (EPS) into their products must continue to monitor the latest regulations to ensure that they are in compliance in each region where their product is sold.

In the early 90's the efficiency of external power supplies, mainly utilizing linear technology, could be as low as 50 % and still draw power when the application was turned off or not even connected to the power supply (referred to as "no-load" condition). Experts calculated that without efforts to increase efficiencies and reduce "no-load" power consumption, external power supplies would account for around 30 % of total energy consumption in less than 20 years. As early as 1992, the US Environmental Protection Agency started a voluntary program to promote energy efficiency and reduce pollution which eventually became the Energy Star program. However, it was not until 2004 that the first mandatory regulation dictating efficiency and no-load power draw minimums was put in place.

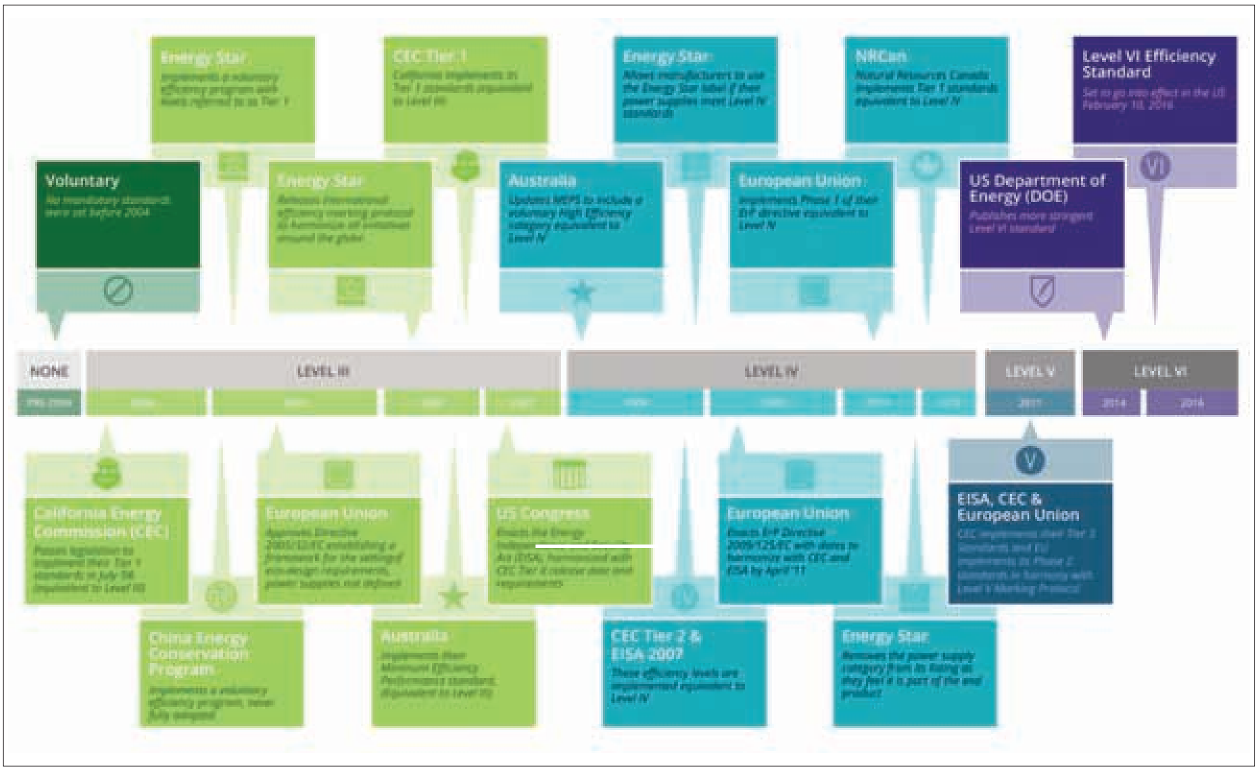
As different countries and regions enact stricter requirements and move from voluntary to mandatory programs, it has become vital that OEMs continually track the most recent developments to ensure compliance and avoid costly delays or fines. While many countries are establishing voluntary programs harmonized to the international efficiency marking protocol system first established by Energy Star, the USA, EU and Canada now have regulations in place mandating that all external power supplies shipped across their borders meet the specified efficiency level IV (Canada and USA) and V (European Union).

Although the United States Department of Energy has established the more stringent Level VI standard, it is not set to go into effect until 2016. Today, Level V will meet or exceed the requirements of any governing body around the globe. Power supply manufacturers indicate compliance by placing a Roman Numeral V on the power supply label as specified by the International Efficiency Marking Protocol for External Power Supplies Version 3.0, updated in September 2013. This latest version of the Protocol provides additional flexibility on where the marking may be placed.

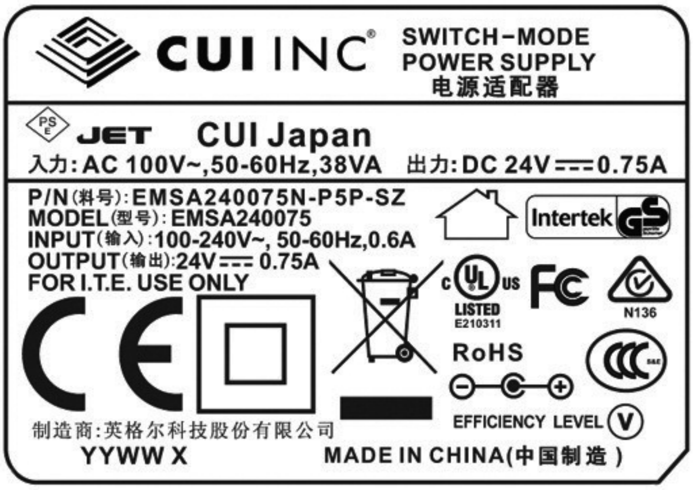
The European Union is currently the only governing body to enforce compliance to the Level V standard, though most external power supply

LEVEL	NO-LOAD POWER REQUIREMENT	AVERAGE EFFICIENCY REQUIREMENT
I	used if you do not meet any of the criteria	
II	no criteria was ever established	
III	≤10 Watts: ≤0.5W of No Load Power 10–250 Watts: ≤0.75W No Load Power	≤1 Watt: ≥ Power x 0.49 1–51 Watts: ≥[0.09 x Ln(Power)] + 0.49 49–250 Watts: ≥84%
IV	0–250 Watts: ≤0.5W No Load Power	≤1 Watt: ≥ Power x 0.50 1–51 Watts: ≥[0.09 x Ln(Power)] + 0.5 51–250 Watts: ≥85%
V	Standard Voltage Ac-Dc Models (>6Vout)	
	0–49 Watts: ≤0.3W No Load Power 50–250 Watts: ≤0.5W No Load Power	≤1 Watt: ≥ 0.48 x Power + 0.140 1–49 Watts: ≥[0.0626 x Ln(Power)] + 0.622 50–250 Watts: ≥87%
	Low Voltage Ac-Dc Models (<6VOut)	
	0–49 Watts: ≤0.3W No Load Power 50–250 Watts: ≤0.5W No Load Power	≤1 Watt: ≥ 0.497 x Power + 0.067 1–49 Watts: ≥[0.0750 x Ln(Power)] + 0.561 50–250 Watts: ≥86%
The term "power" means the power designated on the label of the power supply		

Current performance thresholds for external power supplies



Path from the CEC's 2004 regulation up to the new Level VI standards set to take effect February 2016



Efficiency level identified on the label with a roman numeral I, II, III, IV, V, VI

manufactures have adjusted their product portfolios to meet these requirements. The adjustments are a direct response to the needs of OEM's to have a universal power supply platform for their products that ship globally.

The internationally approved test method for determining efficiency has been published by the IEC as AS/NZS 4665 Part 1 and Part 2. The approach taken to establish an efficiency level is to measure the input and output power at four defined points: 25 %, 50 %, 75 % and 100 % of rated power output.

Not all external power supplies are treated the same and exemptions exist in both the US and the EU.

In the US, Congress has written provisions into section 301 of EISA 2007 that exclude some types of external power supplies. These are devices that require Federal Food and Drug Administration listing and approval as a medical device in accordance with section 513 of the Federal Food, Drug, and Cosmetic Act (21 U.S.C. 360c); power the charger of a detachable battery pack or charges the battery of a product that is fully or primarily motor operated; are made available as a service part or spare part by the manufacturer of an end-product that was produced before July 1, 2008 for which the external power supply was the primary load, but power supplies used for this purpose can be manufactured after July 1, 2008.

The European Union has instituted similar exemptions to the US. External power supplies for medical devices, battery chargers, and service products are exempt. In addition, an exemption exists for low voltage EPS devices. Low voltage external power supply means a unit with a nameplate output voltage of less than 6 V and a nameplate output current greater than or equal to 550 mA.

Moving to level VI

Power supply manufactures, including CUI, are already preparing for the coming transition to the more stringent Level VI standards. Along with tightened regulations for existing adapters, the new standard expands the range of products that fall under the standard such as multiple-voltage external power supplies and products with power levels >250 W.

The new standard also defines direct and indirect power supplies. Direct operated external power supply functions in its end product without the assistance of a battery. An indirect operation EPS is not a battery charger but cannot operate the end product without the assistance of a battery. The new standard only applies to direct operation external power supplies. Indirect operation models will still be governed by the limits as defined by EISA2007.

The compliance date for the new requirements has been set for February 10, 2016. Compliance with the new standard will be regulated from the date of manufacture, so legacy products can still be shipped as long as the manufacture date is prior to February 10, 2016. Labeling requirements will be required to meet the same International Efficiency Marking Protocol for External Power Supplies Version 3.0 as the current Level V standard.

Globally, it is expected that other nations will soon follow suit with this standard. In the EU, the mandatory European Ecodesign Directive for external power supplies is currently going through revision discussions and it is expected to harmonize with most, if not all, of the US standards. It should be expected that countries with existing efficiency regulations in-line with the US, including Canada and Australia, will move to harmonize with the new standard as well.

Outlook

The EPA estimates that external power supply efficiency regulations implemented over the past decade have reduced energy consumption by 32 billion kilowatts, saving $2.5 billion annually and reducing CO2 emissions by more than 24 million tons per year. Moving beyond the mandated government regulations, many OEMs are now starting to

Single-Voltage External AC-DC Power Supply, Low-Voltage		
Nameplate Output Power (Pout)	Minimum Average Efficiency in Active Mode (expressed as a decimal)	Maximum Power in No-Load Mode (W)
$P_{out} \leq 1$ W	$\geq 0.517 \times P_{out} + 0.087$	≤ 0.100
$1 \text{ W} < P_{out} \leq 49$ W	$\geq 0.0834 \times \ln(P_{out}) - 0.0014 \times P_{out} + 0.609$	≤ 0.100
$49 \text{ W} < P_{out} \leq 250$ W	≥ 0.870	≤ 0.210
$P_{out} > 250$ W	≥ 0.875	≤ 0.500

Example of Level VI performance thresholds

demand "greener" power supplies as a way to differentiate their end-products, driving efficiencies continually higher and even pushing the implementation of control technologies that in some cases eliminates no-load power consumption altogether.

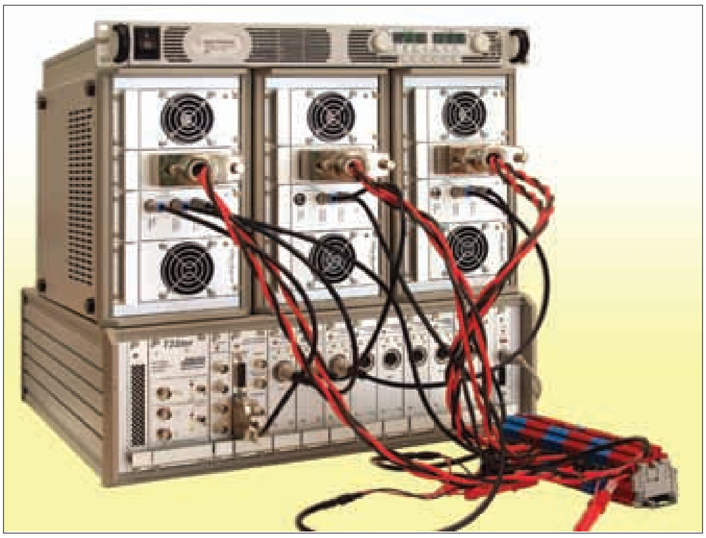
In late 2014, CUI Inc began introducing Level VI compliant adapters to keep their customers one step ahead of the coming legislation. Moving forward, CUI will continue to look for ways to implement the latest energy saving technologies into their external power supplies in order to address market demands and comply with current and future regulations.

www.cui.com

Reliability of IGBT Modules Tested

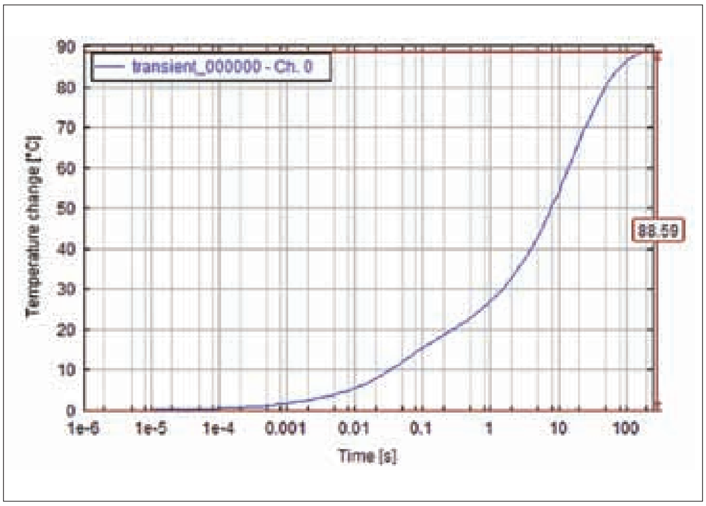
Dissipated heat in the junction is one of the major effects that can influence the reliability of die-attach materials used in an IGBT module. High junction temperatures and high temperature gradients during operation induce mechanical stress, especially where surfaces of materials with different coefficient of thermal expansion are in contact, which may lead to the degradation or the complete failure. Good thermal design and selecting the proper die-attach material for the application is important to avoid premature failures.

The most commonly used method for testing the long-time behavior of die-attach materials is temperature cycling. These tests may be carried out on dummy samples in high volumes; however, such tests are time-consuming and require special environmental chambers.



T3Ster system with three high current boosters and an external Agilent power supply aimed at high current applications such as IGBT measurements

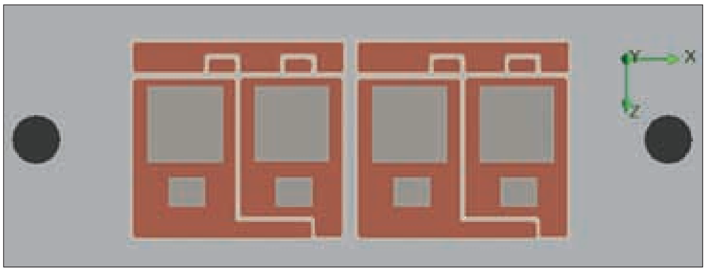
The general consensus is that the most vulnerable parts in high power modules are the bond wires simply because of their large number. However, during testing, the electrical properties may be kept close to constant, and the die-attach material properties response may vary depend on the power applied. As such, it's more effective to run power-cycling tests. These tests are ideal to mimic the lifecycle of a module in an accelerated way because the number of switching cycles corresponding to an IGBT module can be predicted based on the target application. The Mentor Graphics Power Tester (see also "1500 A Power Tester", PEE 4/2014, pages 22 - 24) performs thermal transient tests from one steady-state to another to determine cause of failure for a small sample of IGBTs.



Thermal transient response of the studied IGBT module

Power cycling tests to determine degradation of die-attach

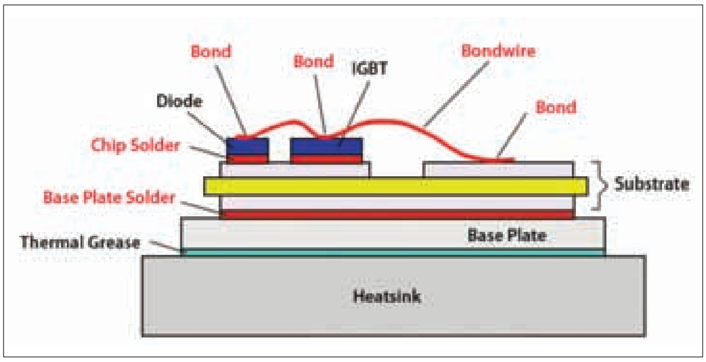
Mentor's engineers wanted to investigate the common failure modes emerging in current IGBT modules, they selected and tested an average power module from a recognized vendor. This experiment did not have enough volume to predict lifetime, but allowed to examine the degradation process.



Layout of the simulation model

As a first step, thermal transient tests on the samples were performed. Trial measurement with T3Ster showed that the thermal transient of the device from steady state to steady state is 180 seconds. The hot steady state was achieved using 10 A of driving current on the device, which was switched to 100 mA sensor current when the data acquisition began.

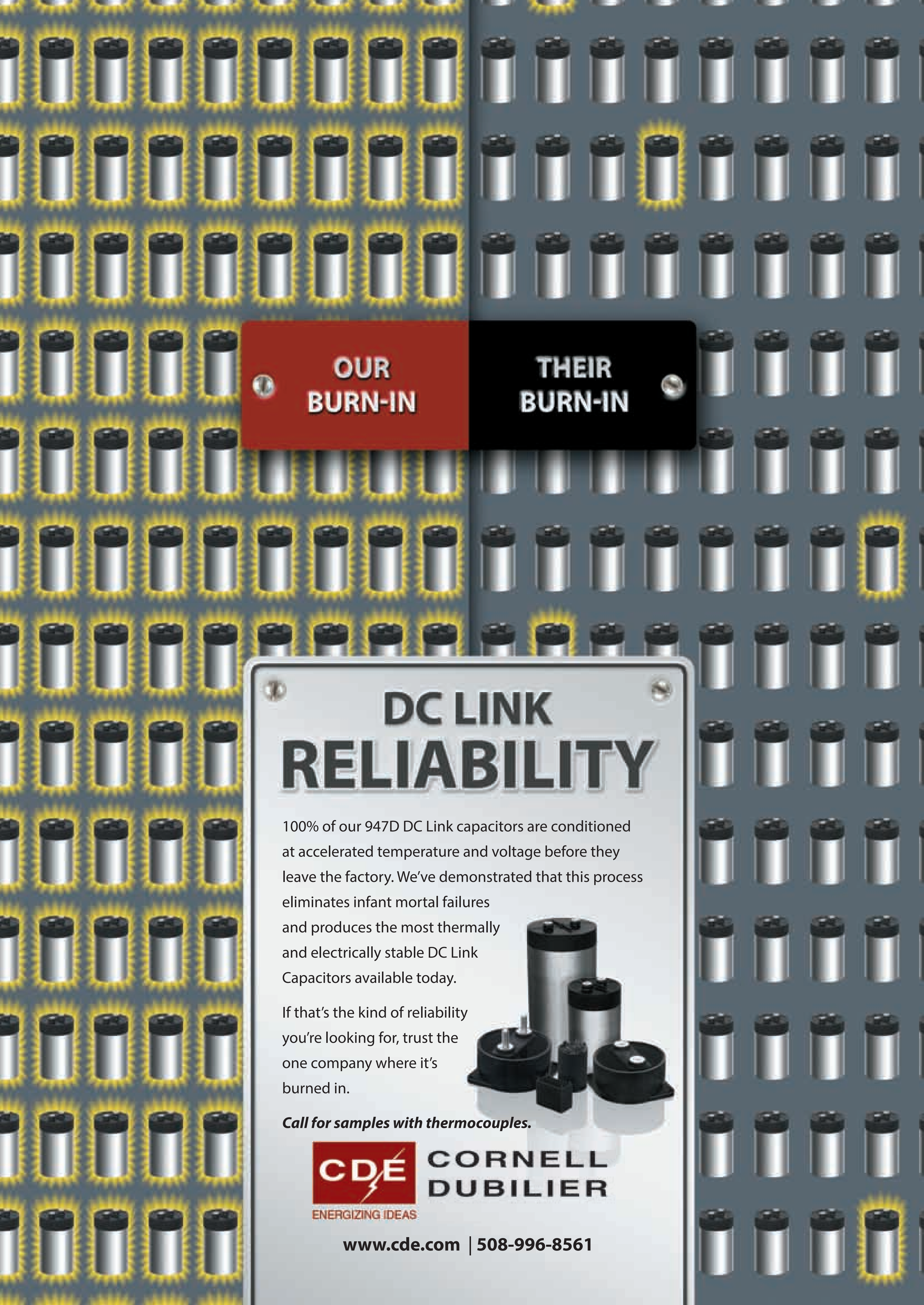
The thermal transient function that describes the initial "healthy" status of the sample. This curve and the corresponding structure function were used as a basis for calibration of a detailed numerical representation of the package. Structure functions are direct models of one-dimensional, longitudinal heat-flow. In many frequently used 3D geometries, structure functions are direct models of the "essentially" 1D heat flow that takes place, such as radial spreading in a disc (1D flow in polar coordinate system), spherical spreading, conical spreading, etc. They can be used to approximately identify geometry/material parameters. The structure functions are obtained by direct mathematical transformations from the heating or cooling curves, which may be obtained either from measurements or from the simulations of the detailed structural model of the heat-flow path.



Cross-section of the tested IGBT module

Thermal simulation model

A detailed 3D model of the module was built and verified so that the temperature distribution inside the structure could be analyzed. The geometric parameters were measured after all devices failed and the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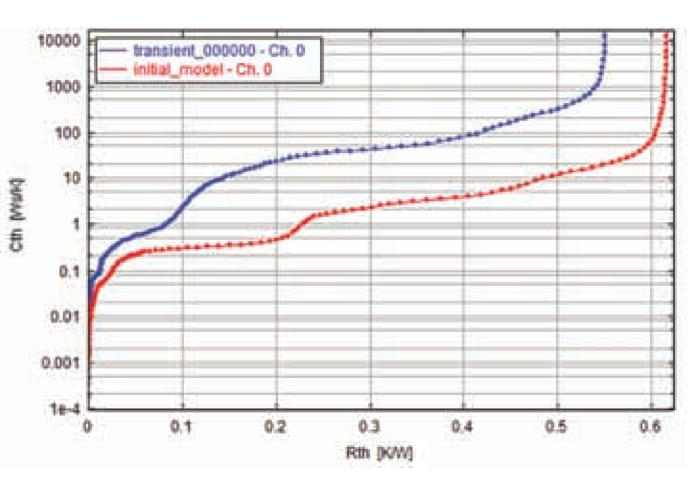


Fitting the structure functions obtained from the thermal transient simulation of the model (red curve) to the structure functions generated from measurements of the real device (blue curve)

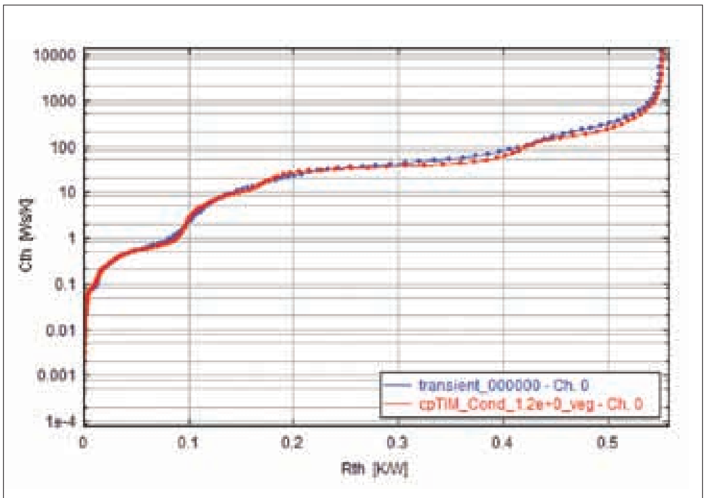
module has been disassembled.

The base-line model, based on the measured geometry and the best guess of the material parameters, showed a significantly different thermal transient behavior than the real device. These discrepancies, however, can be eliminated by calibrating the model, that is, the successive refinement of the model data.

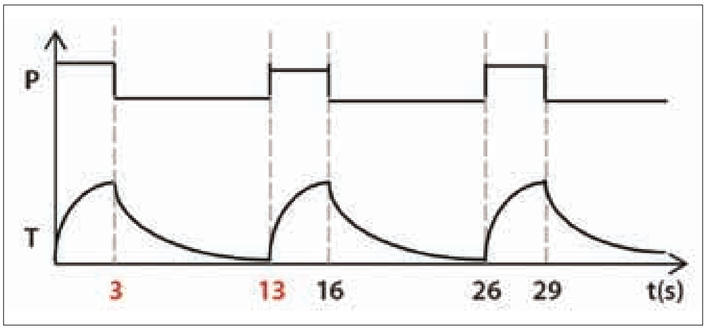
Calibrating of the device began by fitting the internal features of the package; then outward from the package in the direction of the heat flow path, fitting successively the thermal capacitance and thermal resistance values of the different regions. First, the die capacitance had to be properly adjusted by making sure that the physical dimensions of the die were correct and the area of the heat sources was set properly. In this case, the heated area until the capacitance values at the die region overlapped each other on the structure function needed to be increased. Then the thermal resistance of the ceramics layer was set to the appropriate level. With the increase of the thermal conductivity of the ceramics, the length of the corresponding thermal resistance section on the structure function could be reduced to achieve a new fitting section. After that, the bottom copper layer and the thermal interface material (TIM) between the device and the cold-plate to the appropriate thermal conductivity level for a proper match of the curves was set.

Running the device in the power tester

As soon as the initial status of the IGBT's thermal structure was recorded,



Structure function of the simulated (blue) and measured (red) transients after model calibration

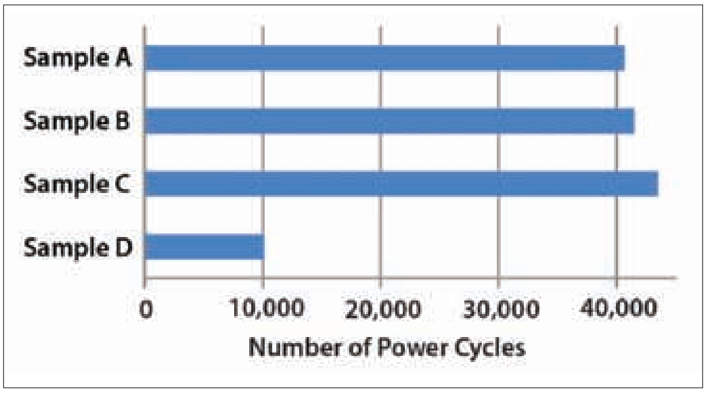


Switching diagram of heating power and junction temperature during power cycling

the device could be exposed to reliability tests to assess its long-term behavior. The IGBT module was fixed to a water cooled cold-plate using a thermal pad, which has poor conductivity compared to most of the thermal pastes and gels, but it showed great thermal stability in earlier experiments, thus it didn't affect the measured results. The cold plate temperature was set to 25°C.

The module under test contained two half-bridge modules, that is, four IGBTs. The thermal transient measurement system was used both for the power cycling and the control measurements. The gates of the devices were connected to the drains, and the half-bridge modules were powered using separated driver circuits. All IGBTs were connected to separate channels of the thermal transient tester equipment.

A 100 K temperature swing on the device under test was applied to accelerate the power cycling process. This value was selected so that the maximum junction temperature would be 125°C. The IGBT module can handle currents up to 80 A, but because of the high voltage drop on the devices, the power rating became the limiting factor. Based on previous trial



Number of power cycles applied until failure of the devices

measurements, 25 A was selected as heating current, thus 200 W of heating power for 3 seconds to heat up the chips to 125°C were needed. The cooling time was set to ensure that the chips would have sufficient time to cool down, and the average temperature wouldn't change during the tests.

The applied heating current and timing remained constant during the whole testing process regardless of the changing voltage drop or increasing thermal resistance. The cooling transient of the devices was recorded in every cycle that was made possible to monitor the junction temperature change continuously. After every 200 cycles, a full-length transient measurement was performed using a 10 A heating current to check the structural integrity of the heat flow path.

Damaged gate oxide

In the experiment power cycling continued until the device totally malfunctioned (short circuit or open circuit), which was the failure criteria. Out of the four IGBT devices tested, one device (sample 3) failed significantly earlier than the others, after just 10,158 power cycles. This premature failure was probably caused by incorrect mounting in the

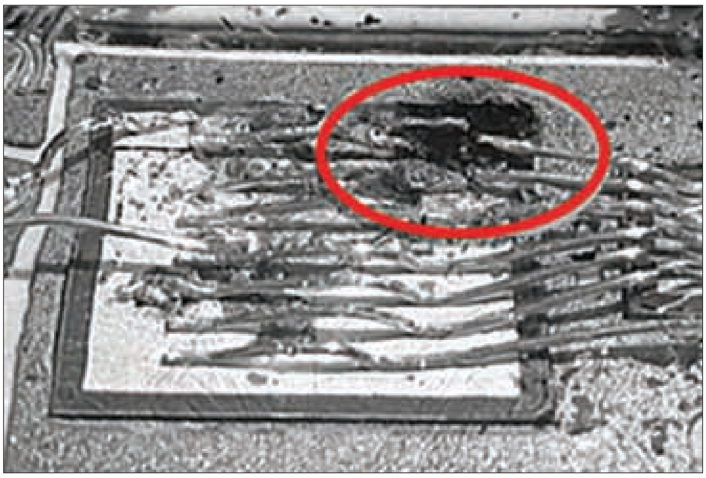


Image of one IGBT chip, illustrating that several bond wires broke during the tests

coldplate or some random error. The other three devices, samples 0, 1, and 2, showed similar behavior and failed after 40660, 41476 and 43489 cycles, respectively. After all the IGBTs failed, the modules were disassembled and the condition of the chips and bond wires were examined. An image of one of the chips illustrates that several bond wires broke during the tests and an area on the chip surface was burned, which was probably caused by the arc when a wire detached while high current was applied.

Despite the obvious defects of the bond wires, the broken bond wires did not cause failure of the devices. All of the chips failed because of overheating and damage to the gate oxide. These effects could later be examined and tracked using electrical tests: the cracking of the bond wires was indicated by the increase of the collector-emitter voltage, and the damage of the gate oxide resulted in the increase of the gate leakage current. When designing IGBT power cycler equipment, these parameters ought to be measured.

The joints between the substrate and the baseplate and the die-attach also need to be investigated to be able to understand the source of the overheating, which is why the calibrated simulation model was needed. The thermal coupling between the adjacent chips was negligible; thus, each chip could be investigated individually.

Because of the short heating time, the maximum temperature elevation of the substrate-base plate joint was 71°C but the die-attach temperature increased by more than 100°C. This result indicated that the most vulnerable point of the structure was the die-attach material.

After approximately 20,000 cycles, the effect of the die- attach degradation was significant, and in about 10,000 cycles, the total junction-to-ambient thermal resistance of the sample doubled as a result of the cycling. After 30,000 cycles, it was impossible to determine the exact thermal resistance of the die-attach layer because of the changes in the heat spreading path.

If the device is exposed to additional power cycles, the long-term reliability of the system also can be tested. In the experiments, three devices out of four consistently lasted for slightly more than 40,000 cycles. Structure functions were taken after every 200th cycle, and the continuous degradation of the die-attach material was clearly visible after approximately 17,000 cycles. From this point on, the total thermal resistance of the sample was monotonously elevating. The increasing junction temperature had other destructive effects; visual observation revealed broken bond-wires and burned areas in the gate region. The burnt gate region was the cause of the complete failure.

www.mentor.com

30th ANNIVERSARY • 1985–2015 APEC 2015 Charlotte NORTH CAROLINA March 15-19, 2015 Applied Power Electronics Conference and Exposition

Focus Again on WBG Technologies and Devices

After our first APEC preview in Power Electronics Europe 1/2015, pages 16/17, we will focus on the plenary session, an event covering the current trends and some subjects of the US industry. From March 15 – 19 APEC's 30th anniversary will be held in Charlotte/North Carolina, attracting delegates and visitors not only from the US.

Challenges in Electrical Power Systems for More Electric Aircraft

This is the subject of the first plenary keynote given by Hao Huang, Chief Technologist and Advanced Technology Leader at GE Aviation.

Because of their higher energy efficiency, lower NOx emission, and less audible noise, more electric aircraft (MEA) has become an inevitable, irreversible trend for the evolution of aviation. This process is called Electrification, and in the last one and half decades, there has been tremendous progress made, e.g., Boeing 787 and Airbus 380. However, there are still significant challenges that block the aerospace industry to fully harvest the advantages of the MEA. One major challenge is weight. Although MEA provides the previously mentioned advantages, the MEA approach does not always achieve lower weight. An important reason is the weight of the power electronics boxes due to complex power electronic circuitries, required EMI filtering, and associated additional cooling. This weight issue diminishes the benefit of MEA on energy efficiency to a considerable extent.

Wide Band Gap (WBG) devices, such as SiC or GaN, are a viable solution to address the weight issue. This presentation briefly discusses the progress made by GE on SiC MOSFET device maturation and reliability, the development of the SiC MOSFET based aircraft electronics subsystems, and some key findings related to how to appropriately implement the SiC in aircraft electric systems. It is clear that WBG enhanced power electronics will accelerate the Electrification process, open up tremendous opportunities for the power electronics industries in aerospace, and cause a substantial evolution in the aviation history.

Power Architectures for the Next Generation of Solid State Lighting

This talk given by David Cox, Director of Alliance Development at Cree, will discuss real world requirements, solutions and challenges and tradeoffs facing power architectures for the next generation of solid state lighting. Applications covered will include street & area lighting; commercial & industrial general illumination; residential lighting, including replacement lamps (A19, GU10, PAR, BR, MR); and automotive lighting. The topics covered will range from high voltage, high power, and high reliability to low voltage (POE) and consumer lighting.

PSMA Power Technology Roadmap

Dhaval Dalal, System Applications Director at ON Semiconductor, will provide a retrospective overview and analysis of past roadmaps and compare their predictions to subsequent results.

The crystal ball that the power electronics industry employs to gaze into the future is the PSMA Power Technology roadmap. This is a regular biennial activity where many industry experts come together to outline the future directions of our industry. The intent of this exercise is to polish the crystal ball and enable future roadmaps to be even more effective.

The results of Power Technology roadmap published in 2015 will also be highlighted in this presentation. The PSMA roadmap activity differs from many commercially available documents as it has contributions from industry insiders with significant technology awareness and depth. Over past few years, the roadmap activity has evolved into a three-dimensional approach where component level trends, application level trends and technology trends are interposed to give a more comprehensive view. The roadmap also captures the industry trends through invited webinars from various industry experts regarding the trends. While casual readers will be able to take away the evolution of pertinent metrics in various application categories, more voracious perusal of the roadmap content will undoubtedly give many more illuminating insights.

Perspectives on Microgrids

As modern society becomes more dependent on digital devices, concerns with climate change prompt greater deployment of clean energy technologies, and the impacts of extreme weather events become more apparent, the electric grid is being asked to do more and more to ensure safe, reliable, and cost-effective delivery of electricity. These changing demands have significant implications for how the grid needs to be designed, control, and protected. Kerry Cheung's presentation, Program Manager and Technical Advisor at the Office of Electricity Delivery and Energy Reliability, U.S. Department of Energy, will share perspectives for the future grid and discuss the potential role of microgrids. DOE experiences with microgrids, future opportunities, and remaining challenges will also be discussed.

Optimizing Performance and Reliability of GaN MOSFET Devices

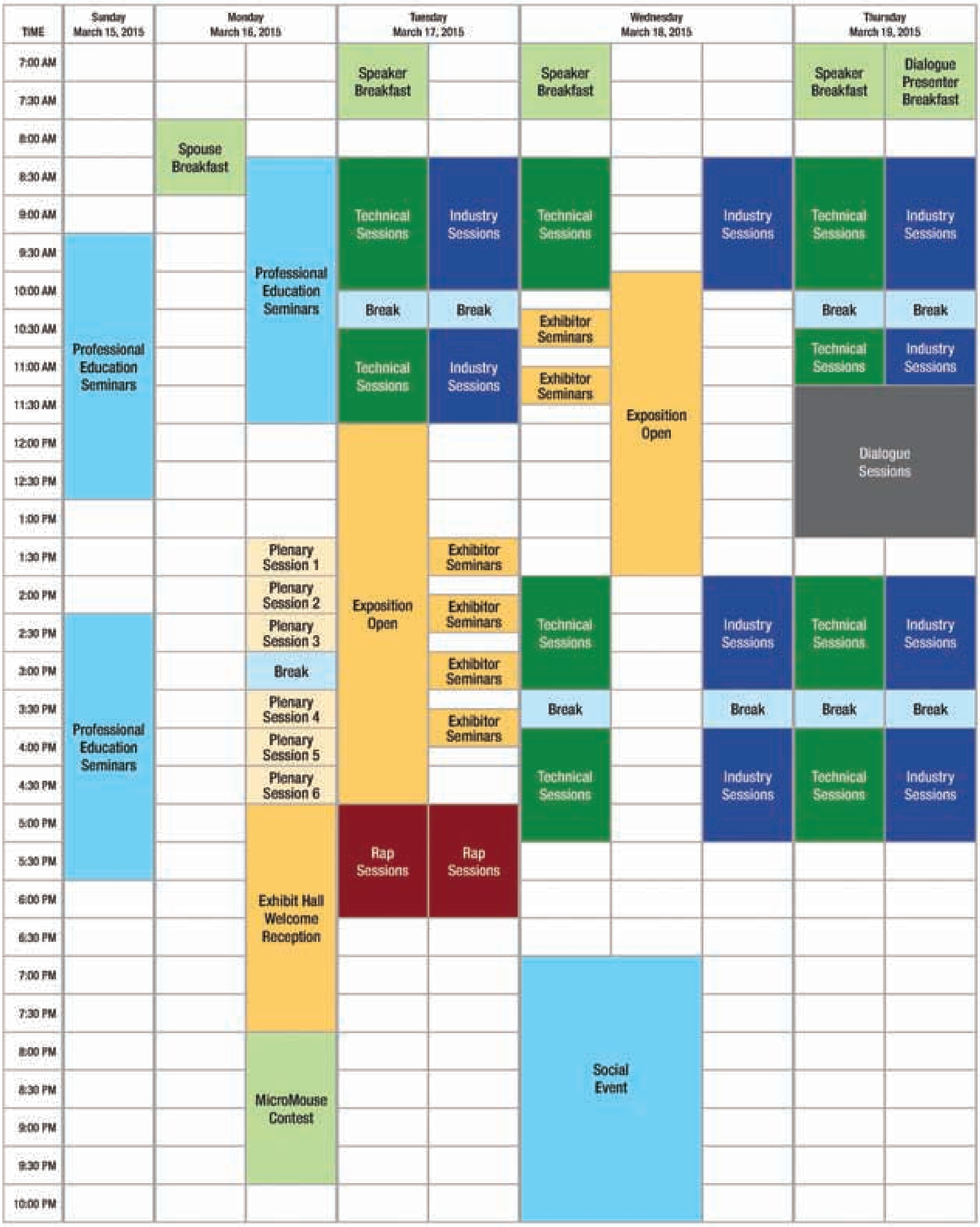
This subject, discussed by Veena Misra, Professor of Electrical and Computer Engineering at North Carolina State University, is certainly of interest by the majority of APEC attendees.

Owing to a high critical electric field and high electron mobility, GaN based lateral Heterojunction Field Effect Transistors (HFETs) are sought after for high voltage power and RF applications. However the device reliability continues to be a critical challenge to be overcome before successful commercialization. In this work, different dielectrics deposited by Atomic Layer Deposition (ALD) have been investigated for improving the threshold voltage stability and dynamic reliability of AlGaN/GaN based Metal-Oxide-Semiconductor-HFETs (MOS-HFETs). This work includes a first-of-its-kind comprehensive analysis of electrical characterization techniques and physics-based models required to evaluate and recommend any dielectric for mitigating surface trapping phenomena in the gate stack or the access-regions. Comparing the efficacy of different methods for characterization of dielectric/AlGaN interface traps, it is found that the popular conductance method has a severely constrained detection limit when the AlGaN barrier offers high resistance to the de-trapping electrons. A capacitance-based method is immune to the issue of barrier resistance, but is still restrictive in its range. To improve the range and accuracy of trap detection, a novel Pulsed-IV-based methodology is developed and demonstrated to be applicable for detecting both shallow and deep traps and implemented on evaluating different high-k and low-k ALD dielectrics. Using physics-based simulation models and experimental data, it is demonstrated that the leakage at the surface of the AlGaN, whether through the passivation dielectric bulk or the dielectric/AlGaN interface, must be minimized to restrict the formation of a “virtual gate” and minimize current collapse. It was also found that an optimal passivation dielectric must create a high density of shallow interface donor traps to quicken the de-trapping of electrons from the “virtual gate” and the recovery of the channel underneath. Combining simulation and experimental results, an optimal set of ALD dielectrics for a reliable gate stack and access-region passivation regions, respectively, was determined and will be discussed. The effectiveness of the resulting optimal dual dielectric passivation stack in mitigating current collapse and ensuring contact isolation is also discussed.

A New Emphasis on Industry Partnerships at Los Alamos

Finding Win-Win outcomes that benefit the nation, that is the subjects of David Pesiri’s talk, Division Leader Richard P. Feynman Center for Innovation at Los Alamos National Laboratory.

On all levels, Los Alamos National Laboratory is being asked to move the needle on issues of domestic and global security, advancing the scientific enterprise on energy concerns, and effective leveraging of the latest technologies and capabilities to bolster US industry and, ultimately, the US economy. To create significant impact demands a new way of thinking about how the Lab engages industry in partnership to produce phenomenal outcomes. The Richard P. Feynman Center for Innovation is leading the change from traditional technology transfer to a robust form of innovation engineering, where its community of business professionals creates collaborations that meet the needs of the Lab and partners, create significant value and impact for the Nation, and that change the world.



APEC’s conference and exhibition schedule at a glance

PCIM
EUROPE

International Exhibition and Conference
for Power Electronics, Intelligent Motion,
Renewable Energy and Energy Management

Technology Trends in Power Electronics

Never before have there been so many applications for presentations at PCIM conference as 2015. The number has grown by 15 % to 310 applications. The scientific and technical level is increasing as well. The Advisory Board headed by the Board of Directors has collocated a program containing 110 lecture presentations and 160 posters. In the following, the authors will highlight briefly some important innovations out of the great international conference program in a short form. **Josef Lutz, Uwe Scheuermann, PCIM Europe Board Members**

Infineon (**www.infineon.com**) shows a new 1000 A/8.5 kV module with "Reverse Conducting IGBTs", where the freewheeling diode is integrated into the IGBT [1]. In transistor operation the former area of the diodes is additionally used, during diode operation additionally the former transistor area. With this integration, a module with the same outline has now a rated current of 1000 A compared to 750 A of the former version. Especially interesting is the capability to strongly control the diode characteristics by the gate. In diode conduction mode, the gate is optimally loaded with -15 V. The flow of electrons is stopped, the p-emitter efficiency becomes high and the voltage drop in conduction mode becomes very low, in the range of only a little bit above 2.5 V. Short before turn-off of the diode, a „desaturation pulse" of +15 V is applied during, for example, 15 µs. An n-channel injecting electrons is formed parallel to the p-doped diode emitter region forms. The p-emitter efficiency now becomes very low. The internal plasma shape of carriers becomes optimal for turn-off with low reverse recovery current maximum. After a short dead time, the IGBT is turned-on and the diode is commutated in reverse direction. This leads to low turn-off losses of the diode (reduced by 40 %) and low turn-on losses of the IGBT (reduced by 34 %). Never before the advantage of a field-controlled diode could be shown in such a perfect way.

PCIM Europe 2015 Conference will provide attendees with the latest achievements in power electronics, in particular power semiconductors such as SiC and GaN

ABB's (**www.abb.com/semiconductors**) "Reverse Conducting IGBT" in planar technology is announced since several times. Now it is additionally offered in the presspack housing [2]. With this integration, the current rating is increased to 3000 A. In the experiment, three devices in series switched 19 kA at a voltage of 9 kV.

Fuji (**http://www.fujielectric.com/products/ emiconductor/products/powerdevices**) introduces with the 7th generation 1200 V an improved IGBT and an improved freewheeling diode [3]. The voltage drop in conduction mode is reduced by 0,3 V to a value significantly below 2 V (150°C). Since 1200 V is the mass application for IGBTs, the contribution to energy efficiency can be estimated to be very high.

Cree (**www.cree.com/power**) has made a 10 kV/20 A MOSFET in in the third generation [4]. It reaches around 100 mΩ·cm2 at 25°C. Compared to a 6.5 kV IGBT, the switching losses are lower by a factor of 40. This MOSFET can by used with a switching frequency of 10 kHz; with a 6.5kV IGBT,

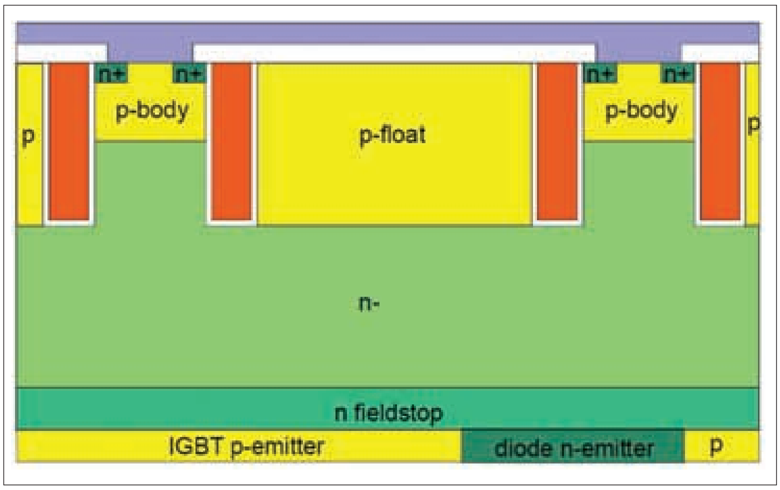


Figure 1: Reverse conducting trench IGBT with integrated diode Source: Infineon

in comparison, one has to operate below 500 Hz (Session SiC High Power, 19.05.2015, 11:00 – 13:00).

SiC devices are becoming mature and are an increasing part of the PCIM program. Also GaN as new material for Power Devices evolves dynamically. A special session [5] with invited lecture presentations is on GaN for automotive applications. A further session is with selected lectures from the applications dealing with the new GaN devices and experiences with the realization of converters with these new devices.

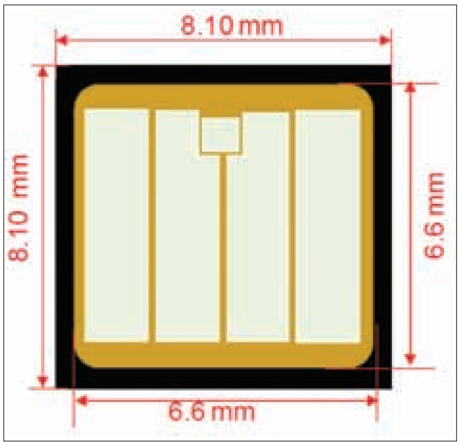


Figure 2: 10 kV / 20 A MOSFET from Cree

Low Inductivity High Power Modules

Hitachi (**www.hitachi-power-semiconductor-device.co.jp**) has developed a low inductive IGBT module 1700 V / 900 A [6]. The internal parasitic inductance is halved, so with clever arrangement in parallel connection the inductance of the system including bus bars can be reduced by 61 %.

ABB Switzerland will present LinPak [7], a new low inductive Phase-Leg IGBT Module with easy paralleling for high-power density converter designs, featuring a new open standard IGBT module topology. The new phase-leg module concept on a footprint of 94 mm x 140 mm is setting a new standard in power density. It features low stray inductance enabling the full utilization of fast IGBT chip-sets and even future full Silicon Carbide switch solutions. In addition the design is made for parallel connection with negligible derating, thus a large range of inverter power can be realized with just one module type.

Also Infineon shows a new power module and shows, that in the high power range now less than 60 nH system inductivity is possible [8].

Also in the range of medium power there are innovations. Infineon has developed a module for double-side cooling in mold-technology, which is especially designed for applications in electromobility [9]. The "spacer" replaces the bond wires in the power path, it introduces additional thermal capacity at the chip topside - the position which is very effective for its action (Figure 4).

The interconnections close to the chip are of

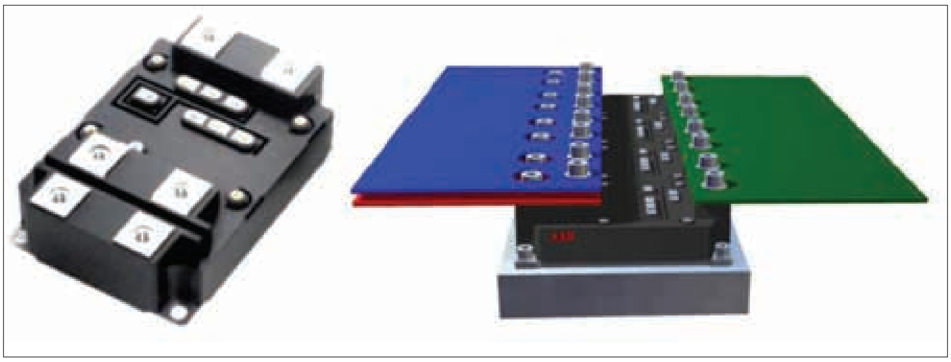


Figure 3: Low-inductive IGBT module 1700V 900A from Hitachi (left), low-inductive bus bar arrangement with an ABB module in identical outline (right)

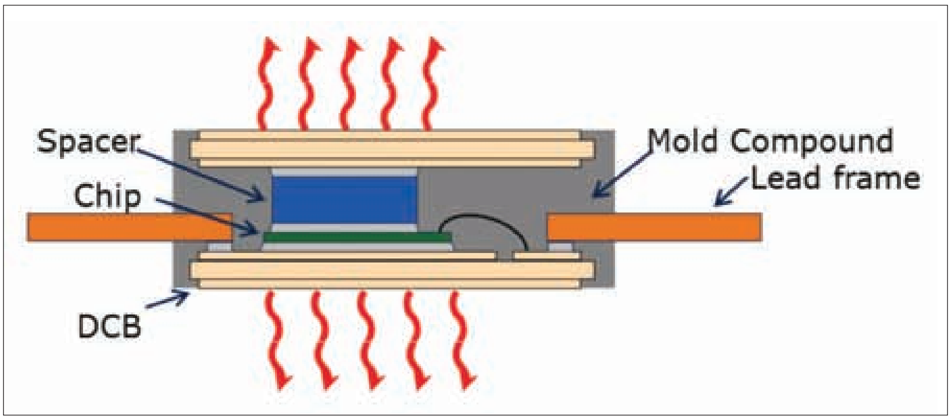


Figure 4: Module for double-side cooling in mold-technology Source: Infineon

fundamental relevance for the reliability of power electronic components. A potential to increase the reliability of Al wire bonds is presented by the TU Berlin [10]. Based on the observation that the lifetime of wire bonds in active power cycling tests decreases with increasing wire diameter, sections produced by laser technology are inserted in the wire bond stitch (see Figure 5). These sections increase the lifetime on the one hand, while they allow to better observe the progress of fractures with an infrared camera in situ during power cycling test on the other.

Interesting results on the impact of surface metallization of DBC substrates on the characteristics of the chip interconnection with classical SnAg3.5 solder are presented by authors from the Imperial College, London [11]. A meta-stable NiSn4 phase is formed during the solder process on substrates with Ni or Ni/Au surfaces, which slowly decays over time and thus reduces the mechanical stability of the solder interface. Measures to suppress the formation this meta-stable phase are discussed.

Semikron (**www.semikron.com**) reports in detail on results of active power cycling tests [12]. They managed to separate the two failure mechanisms, wire bond lift-off and solder fatigue, and determined characteristic parameters for both failure modes. This is a valuable contribution for the theoretical understanding and for improved future lifetime models.

Mitsubishi (**www.mitsubishielectric.com**) also discusses improved wire bonds and Ag diffusion sintering, which enhance enhanced the active power cycling lifetime of modules considerably [13].

Other aspects of reliability are also examined in the conference program. Mitsubishi provides new results on the stability of IGBT modules against humidity, which penetrates standard housing material and insulation gels [14]. The combination of a new insulation gel with an improved chip passivation improves the humidity resistance significantly, as is demonstrated by a 5.2 kV DC biased test on a 6.5 kV power module.

New results on cosmic ray failures

Power electronic components can be destroyed by cosmic ray incidents; the observed failure rate is a function of the applied DC link voltage. Application engineers target for low numbers of accumulated failures during the lifetime of their systems and they want to select the DC link voltage accordingly. However, exact data on cosmic ray failure rates are rarely published in technical literature, since most manufacturers only supply such data for selected customers on the basis of non-disclosure agreements (NDAs). Therefore, the publication of new quantitative results at this conference are of special interest. ST Microelectronics (**www.st.com**) together with the University of Calabria present comparative data on 1200 V Si IGBTs and SiC MOSFETs [15] (see Figure 6). The failure rate of the SiC MOSFET at 92 % of the nominal blocking voltage is comparable with the failure rate of a Si IGBT at 75 % of the blocking voltage. The failure rates drastically increase when a threshold voltage of 70 % and 85 % of the nominal blocking voltage is exceeded for Si IGBTs and SiC MOSFET, respectively.

Thus, the SiC MOSFET can be utilized with 15 % higher DC link voltages compared to Si IGBTs without the risk of higher cosmic ray failure rates. These first quantitative results allow a better evaluation of solutions based on SiC technology than the often stated general claim, that SiC devices are cosmic ray resistant in contrast to Si devices. However, a contribution from Semikron in the same conference session demonstrates that it is possible to design Si diodes with a cosmic ray stability up to 100 % of the rated blocking voltage [16]. This confirms that cosmic ray stability is strongly affected by the implemented device technology, and that this subject remains and interesting topic.

Power electronics can stabilize power grids

Another important focus of the conference is the stabilization of power grids facing a growing contribution of regenerative energy sources. Fluctuations of meteorological conditions result in variations of generated power, supplied by photovoltaic and wind generator systems in particular. These fluctuations necessitate energy storage elements, which are coupled to the grid by frequency converters for stabilization. Sanken Electric together with Nagaoka University of Technology (Japan) introduce a flywheel energy storage for this purpose, which is coupled to the grid through a matrix converter [17]. The system features a high expected lifetime and an excellent energy efficiency. Other contributions from the University of Parana (Brasil) and from the University of Tel Aviv (Israel) propose different control strategies for converters, which have to ensure stability in presence of transient disturbances and in weak grid structures.

A dedicated session focusses on the subject of high voltage DC transmission, with contributions on different converter topologies and a new design proposal for a HVDC circuit breaker by the Karlsruhe Institute of Technology [18].

These selected topics support the general impression, that the PCIM Europe conference continues to grow in professional quality as well as in international relevance. Manufacturers of power

LEFT Figure 5: Image of a standard wire bond stitch (top) and of a stitch with sections produced by laser technology (bottom) Source: TU Berlin, Research Centre for Microperipheric Technologies

RIGHT Figure 6: SiC MOSFET destroyed by cosmic ray failure Source: ST Microelectronics

electronic components and systems often select this conference to introduce technological innovations to a professional audience for the first time. Another special feature of the PCIM conference is the strong focus on reliability, which makes it even more attractive to all experts from power electronic applications.

More general information on the PCIM Europe 2015 program have been provided in PEE 1/15 [19].

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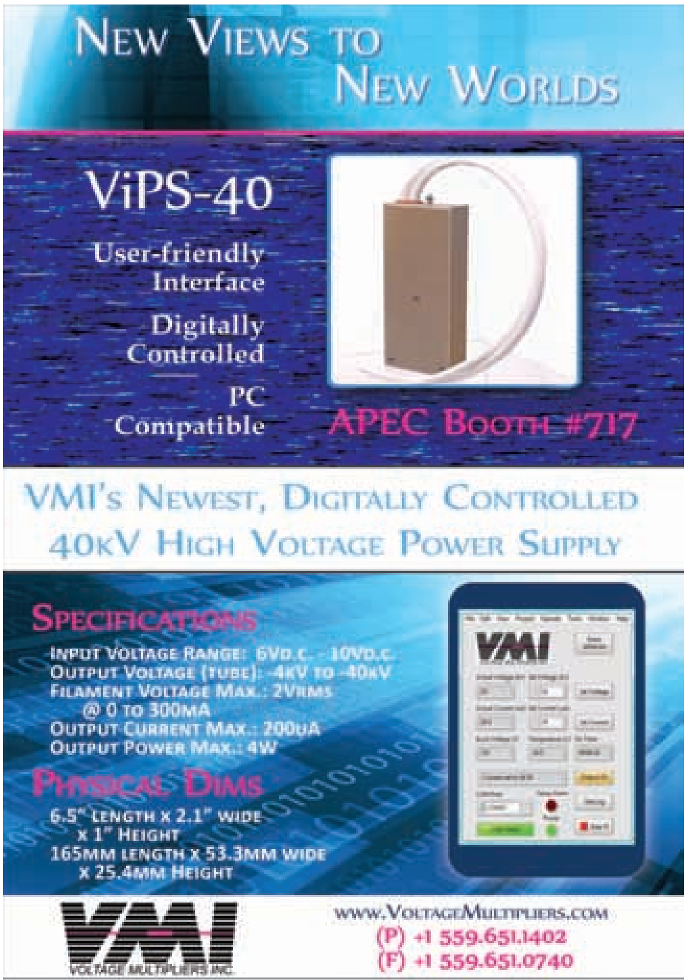


How 600 V GaN Transistors Improve Power Supply Efficiency and Density

High performance power supplies today are already very efficient. For at least two years, "Titanium" efficiency server power supplies have been announced with greater than 96 percent overall energy efficiency at half load (per 80 PLUS®* standards). These power supplies achieve this high efficiency level using today's available technology including high performance Si FETs and SiC Schottky diodes. So what comes next? With several companies announcing the availability of GaN on Si 600-650 V transistors, how will these new devices take power supplies to even higher levels of efficiency, and density?

Eric Persson, Executive Director GaN Applications and Marketing, International Rectifier, an Infineon Technologies Company, El Segundo, USA

To begin, consider the limitations of existing Silicon FET technology, and what power supply designers would want in a more ideal switching device. Controlling conduction loss is straightforward: a larger area FET or several FETs in parallel will reduce effective $R_{DS(on)}$ to negligible levels. But there is of course a tradeoff here. More FETs also means more capacitance (and, therefore, charge), thus increasing frequency-dependent switching losses. So for a given frequency range, power supply designers must balance conduction and switching losses to achieve the overall lowest total loss. Moreover, the dynamic characteristics of a FET body diode have a significant impact on frequency-dependent losses in certain topologies. This is where new technologies like GaN can add value. For a given $R_{DS(on)}$, GaN switches have lower output charge Q_{oss}, lower gate charge Q_g, and vastly lower reverse-recovery charge Q_{rr}, than the best available Silicon FETs. Moreover, GaN devices have a much more linear charge versus voltage characteristic than superjunction FETs (superjunction is the dominant high-voltage FET technology used in power supplies today). The linearity of Q_{oss} plays a key role in reducing deadtime and, therefore, enabling high efficiency at high frequencies.

New solutions ahead

The new breed of GaN devices are High Electron Mobility Transistors (HEMTs), which have been described in numerous publications recently. To be cost-effective, HEMTs are manufactured on Silicon substrates, rather than Silicon Carbide or pure GaN which are both easier, but considerably more expensive.

HEMTs are lateral devices that can be manufactured as either enhancement or depletion-mode transistors [1]. For power electronic designers, a normally-off power switch (meaning the FET is off when the gate voltage is zero) is much preferred over a normally-on device, even if the normally-on device could provide some additional performance. This is because normally-on devices make it challenging to control current during power-up and power-down for example, requiring a master enable switch or a pre-bias arrangement to make sure the normally-on devices don't turn-on randomly when the control circuit is booting-up or powering-down. Early 600 V GaN HEMTs developed for power electronics were depletion-mode devices. To solve the normally-on issue, the depletion-mode HEMT was combined with a low-voltage Silicon MOSFET to form a normally-off hybrid device known as a GaN cascode [2,3] (see Fig. 1). Enhancement-mode GaN HEMTs at 600 V (which are intrinsically normally-off) were perhaps

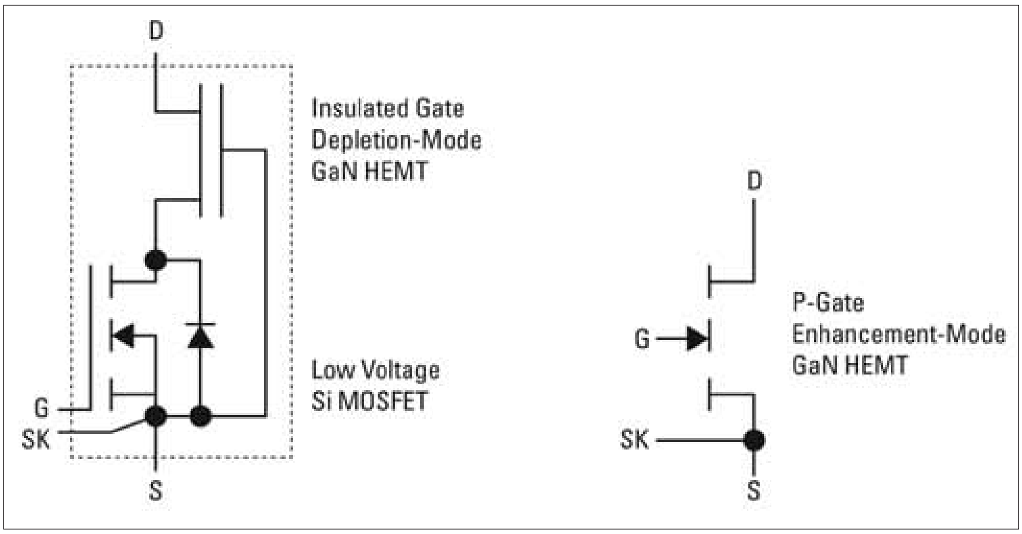


Figure 1: Normally-off 600 V GaN transistors: Cascode and enhancement-mode HEMT

Parameter 600 – 650 V, 100 mΩ	Best Si Superjunction	GaN Transistor range
Typical Q_g	40 nC	3 – 12 nC
Typical Q_{oss} @400V	260 nC	24 – 60 nC
Typical E_{oss} @400V	4.5 µJ	3.7 – 7.5 µJ
Typical Q_{rr}	7 µC	0.0 – 0.06 µC

Table 1: Comparison of Si Superjunction versus GaN transistor key attributes (normalized to 100 mΩ)

more challenging to develop, but are also now just becoming available on the market.

Enhancement-mode and cascode are two different approaches to providing a high performance 600 V normally-off GaN-based switch. While there are differences between the two devices (mainly in the gate drive circuit and the reverse conduction characteristic), both devices provide vastly improved "body diode" performance Qrr, and significantly lower Q_{oss} and Q_g compared to the best available Silicon FETs with similar voltage and $R_{DS(on)}$ ratings. The key attributes of these devices are outlined in the comparison chart above. The data is gathered from recently published articles, papers and datasheets, and normalized to 100 mΩ typical $R_{DS(on)}$ assuming R x Q product is constant. It is not necessarily representative of a particular device, but shows the performance trends between these technology platforms from multiple vendors (see Table 1).

In search of higher efficiency

How do these attributes translate into a benefit for power supplies? The answer is that it depends strongly on the topology. For example, consider traditional boost PFC, which is the most common PFC circuit used today for server power supplies (Figure 2): this is a unipolar topology, so the FET only conducts current in the forward direction – the body-diode is never used. Since this topology is mostly operated below 100 kHz, the gate charge losses are relatively low, so any benefit in Qg is minimal. The two dominant parameters that most affect efficiency are $R_{DS(on)}$ for conduction losses, and the energy dissipated each switching cycle due to the discharge of Q_{oss} when the FET turns on (E_{oss}).

This is where things get confusing: even though the Q_{oss} of the GaN HEMT is significantly lower that the best superjunction, the E_{oss} (the energy stored in C_{oss}) difference between superjunction and GaN is much smaller. The lowest E_{oss} superjunction can be better than cascode GaN, but not as good as enhancement-mode GaN. This paradox occurs because the bulk of the charge stored in superjunction is injected at low voltage (<50 V). Above this, from 50 V to 400 V, the effective charge is lower, but the energy is much higher since

$$dE = \frac{C(V)}{2} dV^2 \qquad (1)$$

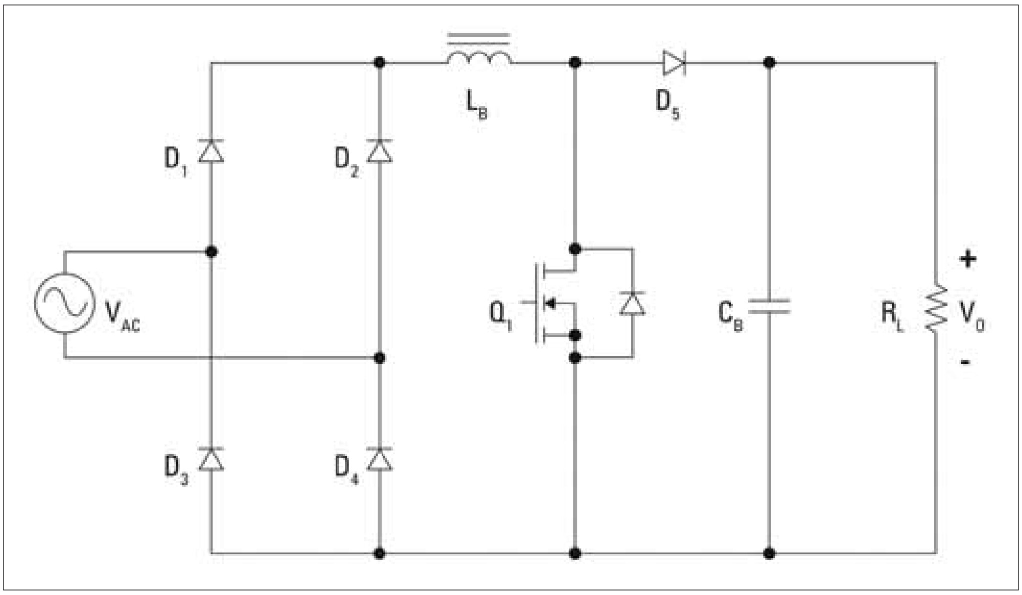
(note the V^2 term and the value of C is a function of V). As a result, even though the charge Q_{oss} at 400 V is 5 to 10x lower for GaN than SJ, the *energy* difference is much smaller: the best superjunction is better than cascode GaN and within 15 % of enhancement-mode GaN (see Table 1). The net result is this: if you simply drop-in the same $R_{DS(on)}$ GaN switch into a high-performance superjunction socket like this PFC example, the overall efficiency change is barely measurable.

To get to higher levels of efficiency, one must look more closely at how power loss is distributed in each topology: The main source of loss in traditional boost circuit is not typically from the switch – loss is dominated by the input bridge rectifier which always contributes two (2) diode drops over the entire line cycle.

To utilize the full benefit that GaN transistors offer, consider instead the totem-pole bridgeless boost circuit shown in Figure 3. In this topology, there is no input bridge rectifier, and, therefore, no diode drops (except 1 briefly during deadtime). The low-frequency half-bridge on the right flips the polarity of the line every half-cycle, so switching loss is negligible, only conduction loss matters (this can, therefore, be low cost superjunction). The half-bridge on the left operates at high frequency (typically Continuous Conduction Mode CCM in the 50 – 100 kHz range), with one transistor serving as the boost switch, and the other as the synchronous rectifier – and they swap roles each half-cycle. Besides eliminating all diode voltage drops, this topology has the additional advantage that it can be operated in CCM, CrCM, DCM and even ZVS mode, which enables much higher operating frequency while maintaining outstanding efficiency.

The totem-pole bridgeless boost is not a new topology; it has been around for many years. But until now, the high

Figure 2: Traditional boost PFC circuit (typically Q1 is superjunction and D5 is SiC Schottky)



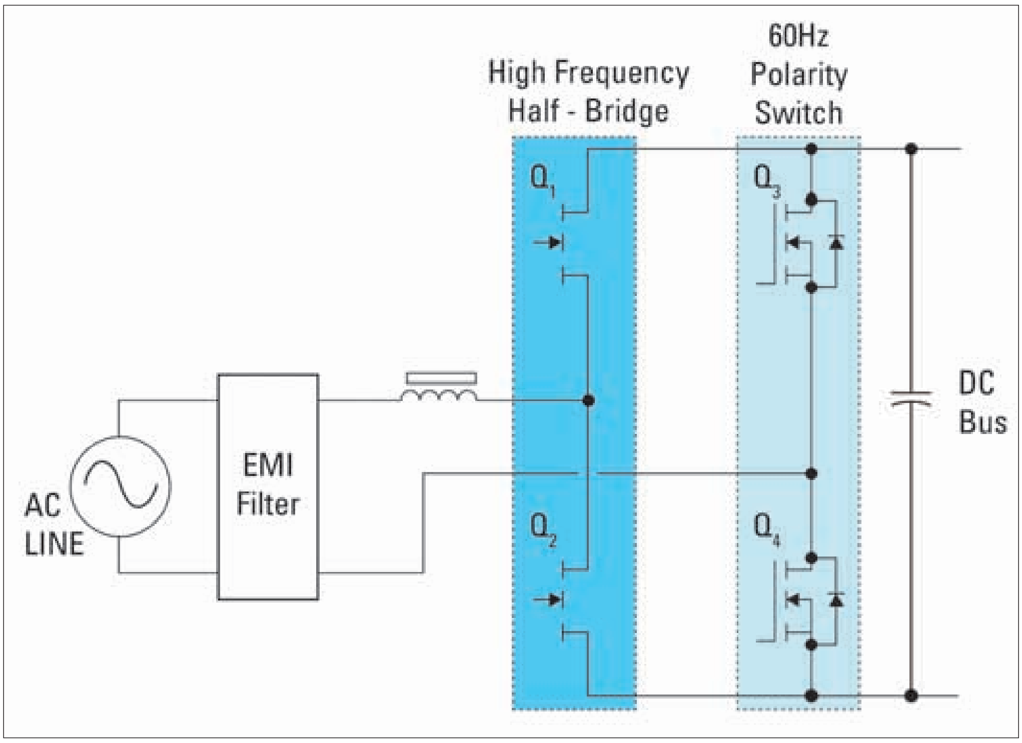


Figure 3: Totem-pole bridgeless boost topology (full-bridge, no diodes)

performance FETs (with low or zero Q_{rr}) have not been available to enable practical implementation. Now with GaN transistors in this topology, several papers have recently reported energy efficiency of the PFC stage exceeding 99 % at standard operating frequencies in CCM. Moreover, a recent CPES presentation from Virginia Tech demonstrated this topology operating in ZVS mode into the MHz range, also exceeding 99 % peak efficiency [4]. This level of performance is quite compelling, and will clearly drive development in the next generation of high performance, high density power supplies using GaN transistors.

The isolated DC/DC stage in power supplies can similarly benefit from GaN transistors. But just like the PFC example above, the benefit is not fully realized by simply dropping a GaN transistor into a FET socket in an existing power supply design, especially in hard-switching unipolar topologies where superjunction already does very well (Flyback, two-transistor forward). The topology, control strategy, magnetics, and operating frequency all need to be considered in the overall design when optimizing for GaN devices. GaN is particularly well-suited for soft-switching and resonant topologies like LLC half and full-bridge, and ZVS phase-shifted full-bridge. The low charge of GaN devices reduces the circulating currents necessary to achieve soft switching, reduces deadtime and therefore rms currents, and reduces gate drive power, while still enabling efficient operation at higher frequencies with smaller passive components [5].

Conclusion

Power supply designs can benefit from GaN transistors now using existing controllers and drivers for LLC and ZVS Phase-Shifted Full-Bridge topologies, operating efficiently at frequencies extending beyond the reach of superjunction. Look for advanced controllers for totem-pole bridgeless PFC and even higher frequency resonant and soft-switching topologies to compliment a broadening portfolio of GaN transistors in the future. By combining these topologies with state-of-the-art drivers and GaN transistors, tomorrow's power supplies will be able to take full advantage of the efficiency and density gains made possible by high voltage GaN transistors.

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SiC and GaN Semiconductors in Modules for Higher Efficiency

With the increasing availability of new semiconductor materials such as SiC and GaN the opportunity to design higher switching frequency circuits at higher power levels has become possible for power electronics design engineers. Both SiC and GaN devices exhibit lower switching losses and higher switching speeds compared to existing Si devices. SiC offers the added advantage of higher operating junction temperatures. But present packaging limitations such as wiring inductance, module materials and bonding techniques prevent full exploitation of the operating temperature range and the maximum switching frequency advantages offered by these new semiconductor materials. This article discusses the advantages and disadvantages of using modules with SiC and GaN semiconductors in high efficiency and compact light weight applications. **Jerry Moudilos, Field Application Engineer, Vincotech, Munich/Unterhaching, Germany**

Existing low inductance module designs and wiring techniques using SiC and GaN semiconductors allow existing modules to be used efficiently with switching frequencies up to 150 kHz. Higher switching frequencies provide the designer with the ability to decrease the size, weight and cost for isolation and filtering components such as transformers, inductors and capacitors in applications which require compact and light weight designs. An added advantage of these semiconductor materials is their lower switching losses which allows their use in designs requiring higher efficiencies.

Applications requiring higher efficiency

In most cases, designers are required to meet minimum system efficiency levels for their designs. These minimum efficiency levels are becoming increasingly higher and more difficult to achieve. When these efficiency levels cannot be achieved by topology selection or by paralleling switching devices, designers may decide to replace existing Si devices with SiC or GaN devices to lower their switching losses. In these cases the switching frequency may remain the same as the original Si design to prevent redesigning the isolation and filtering components. The disadvantage of using more expensive SiC and GaN devices may be justified to meet these higher efficiency objectives.

An ROI or simple payback period calculation can be made to determine if the higher initial cost for the SiC and GaN devices will be returned over the operational life period of the product. In addition to the energy savings, cooling

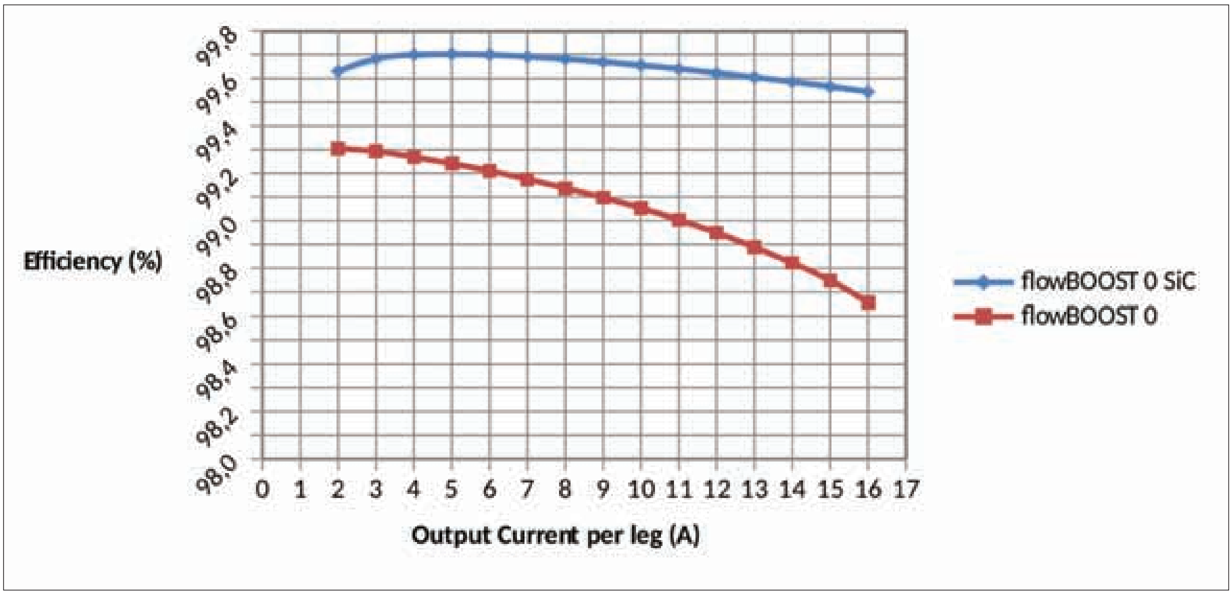


Figure 1: Efficiency comparison between flowBOOST 0 SiC and flowBOOST 0 modules

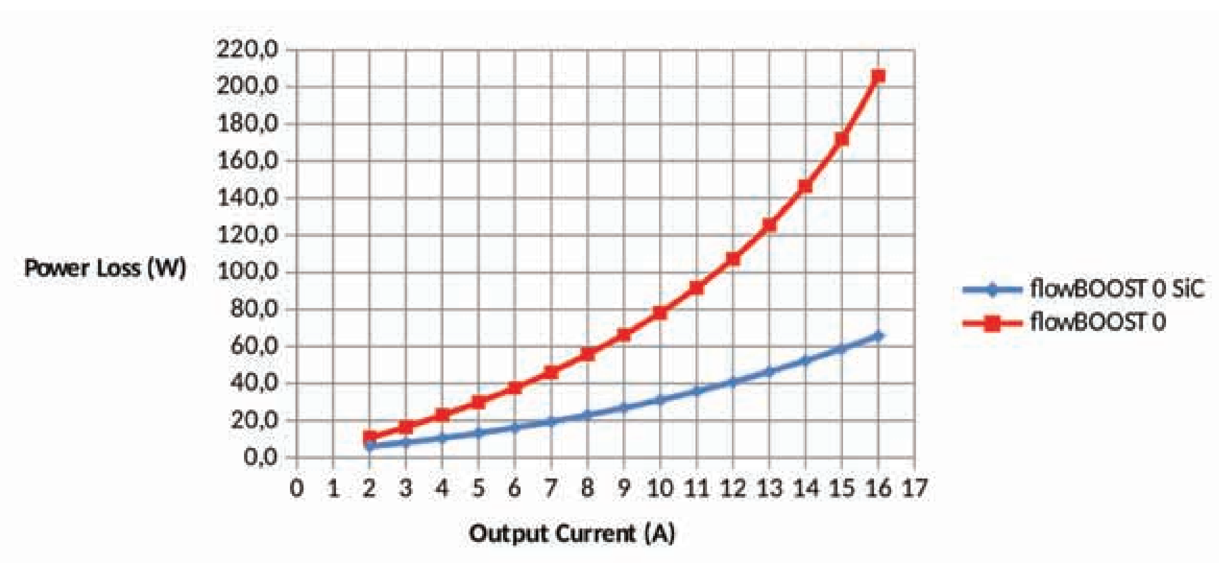


Figure 2: Power loss comparison between flowBOOST 0 SiC and flowBOOST 0 modules

requirements can be decreased since lower switching losses will result in cooler junction temperature when SiC and GaN devices are used at lower switching frequencies. The designer may decide to size down their thermal design to save size, weight, cost and run the module at higher temperatures or keep their existing thermal design and run the module cooler which will prolong the lifetime of the product. This decision will depend on the design's thermal derating criteria and the product's specified life expectancy.

Practical design example

As an example, we can consider the following Si IGBT boost stage design and comparison with an equivalent SiC MOSFET design. The preliminary boost design used Vincotech's flowBOOST 0 Si IGBT based module (V23990-P629-L49) in an application with the following operating conditions:

V_{in} = 500 Vdc, V_{out} = 900 Vdc @ 10 A per leg, R_{gs} = 4 Ω, F_{sw} = 20.0 kHz, $T_{heatsink}$ = 80°C

Using Vincotech's IES2 module simulator, these design and operating conditions resulted in the following output, losses, efficiencies and junction temperatures:

P_{out} = 18.0 kW, Losses = 86.8 W per leg, Efficiency = 99.053 %, Tjmax = 129.9°C

Higher efficiencies were required and the decision was made to replace the Si IGBT module with a SiC MOSFET module. The simulation was repeated with the flowBOOST 0 SiC MOSFET based module (PZ12B2A040ME01-M330L63Y) using the same operating conditions as were used for the Si module. The IES2 simulation software obtained the following results:

P_{out} = 18.0kW, Losses = 31.1 W per leg, Efficiency = 99.655 %, T_{jmax} = 92.2°C

The efficiencies and losses over different loads for the SiC and Si modules were simulated using IES simulator and are shown in Figures 1 and 2.

Both plots show the flowBOOST 0 SiC module has higher efficiencies and lower losses compared with the flowBOOST 0 module and that these differences increase as load current increases.

Although the 55.7 W per leg power saving using the flowBOOST 0 SiC module may seem small, this saving needs to be considered over the operational lifetime of the product. For example, each flowBOOST 0 SiC module consists of two boost stages which will double the power savings to 111.4 W. Assuming this boost converter is used in a solar PV application which will be operating at these operating conditions for 3 hours per day and the contract price of electricity is 0.20 €/kWhr, the additional revenue realized by the solar inverter over 15 years of operation is € 365.95. A more important figure of merit is the payback period which defines the amount of time required to recover the additional cost of choosing the more expensive flowBOOST 0 SiC module over the lower cost flowBOOST 0 module.

Presently, the cost of the flowBOOST 0 SiC module is € 30.29 more than the cost for the flowBOOST 0 module. In this example, the additional cost of selecting the higher efficiency flowBOOST 0 SiC module will be recovered in 1.24 years by the added revenue generated due the lower PV inverter losses. More detailed calculations can be performed which take into consideration the portion of the product's final price which is attributed to the power module and the cost of money if the product was purchased and financed through loans. Exact operating conditions for PV solar inverters will vary for different installation sites. The effects of these site specific parameters should also be considered to obtain more realistic payback periods.

Another design approach to is to determine the additional price one is willing to pay for these higher efficiencies. Payback period can be selected to be aggressive (less than 2 years), moderate (3-5 years) or less aggressive (5+ years) depending on the lifetime of the product and the market's focus on price. Given the energy savings per year, the additional cost one is willing to pay for the SiC devices can be approximated for a desired payback period. In general, if more aggressive payback periods are required, higher prices should be paid for modules with higher efficiency gains. If less aggressive payback periods are acceptable, lower prices can be paid for modules with lower efficiency gains. In either case, comparative simulations should be performed to obtain the new losses and efficiencies which are necessary to calculate the energy savings and payback periods.

Applications requiring smaller and lighter products

Designers in these cases increase the design's switching frequency to decrease the size and weight of the isolation and filtering components to meet the desired size and/or weight requirements. In certain applications such as motor drives the gains using this design strategy are minimal. Inverters for solar applications, battery chargers and power supplies on the other hand may achieve substantial space, weight advantages with higher switching frequencies. Operating expenses will increase due to the higher switching losses but these costs could be offset if the application is mobile such as a portable variable frequency generator or a portable power supply.

An added advantage of switching at higher frequencies is faster feedback loop responses to load changes which are desirable for power supplies but of little advantage for larger motor drives other than to minimize over- and under-voltages. The designer of these applications may choose SiC and GaN devices to achieve the higher switching frequencies required to obtain the smaller size and lighter weight targets required. Although losses will also increase at higher switching frequencies for SiC and GaN devices, these losses will be much less than those exhibited by Si devices.

For example, if it is determined that the flowBOOST 0 Si IGBT design used in the PV inverter design described above needs to be switched at 60 kHz instead of 20 kHz to achieve the desired size and weight reductions, the simulated losses will increase from 86.8 W per leg at 20 kHz to 253.34 W per leg (506.68 W per module) at 60 kHz. These higher losses will force the flowBOOST 0 module to operate at a prohibitive junction temperature of 265.5°C if the thermal designed for the lower switching frequency is left unchanged.

To maintain the design's maximum derated junction temperature specification, additional cooling requirements such as larger heatsink size and higher airflow will be required for the flowBOOST 0 module to operate at this higher switching frequency. The additional cooling effort could offset any size and weight advantage derived from the smaller filter components. If the flowBOOST 0 SiC MOSFET module is used in this higher frequency design, the losses at 60 kHz will be 46.36 W per leg or 299.73 W less per leg (599.46 W per module) than the flowBOOST 0 module design and the component junction temperatures will be 104.5°C. Using the flowBOOST 0 SiC module in this case will help decrease the size and weight of the filter components without increasing the size of the heatsink and fans required for the original 20 kHz design.

ROI and payback period calculations for these smaller size and lighter weight designs can be performed but are complicated by the fact that the savings are not solely dependent on electrical considerations such as component costs and the cost of electricity. In the case of mobile applications, non-electrical operational parameters such as how often and how far the product will be moved as well as the mode of transportation used will result in fuel savings and will differ for each application.

Conclusion

SiC and GaN semiconductor switching characteristics allow designers to benefit from lower switching losses and higher switching frequencies. These characteristics allow designers the flexibility to use the same switching frequency to increase system efficiencies, or to increase the switching frequency and minimizing the size, weight and the cost of filtering components. Efficiency and loss differences between Si and SiC modules can easily be obtained with Vincotech's IES simulator which can be used to perform ROI and payback period calculations to determine if the selection of these higher cost SiC devices was justifiable for the application.

Through System Thinking Designing Reliable High-Power IGBT Modules

Infineon has a long history of setting international standards for IGBT modules. System thinking is one of the biggest drivers in search for new technologies. This article provides insight into the development of a new flexible high-power platform. **Thomas Schütze, Georg Borghoff, Matthias Wissen, Alexander Höhn, Infineon Technologies AG, Warstein, Germany**

In 1993 the first IGBT High Power Module (IHM) with blocking voltages up to 1.7 kV was launched. Subsequent advancements were the development of the IGBT High Voltage Module (IHV) family for voltage classes up to 3.3 kV and, with the availability of 6.5 kV chips, the launch of the IHV 6.5 kV housing in 1999. With the PrimePACK™ launched in 2006, a flexible module with high-current ratings in dual configuration captured the 1.2 and 1.7 kV market. All designs were available for licensing by other suppliers, the same applies to low- and medium-power modules such as Easy, Smart, Econo and EconoPACKTM+. Across multiple generations of chip technology, the designs initially developed by Infineon and licensed by multiple suppliers have found their way into countless applications and are widely spread across the world.

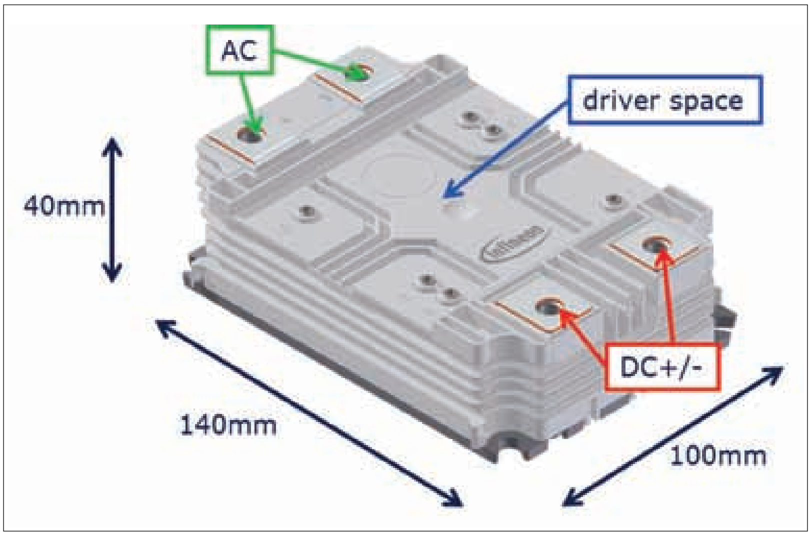
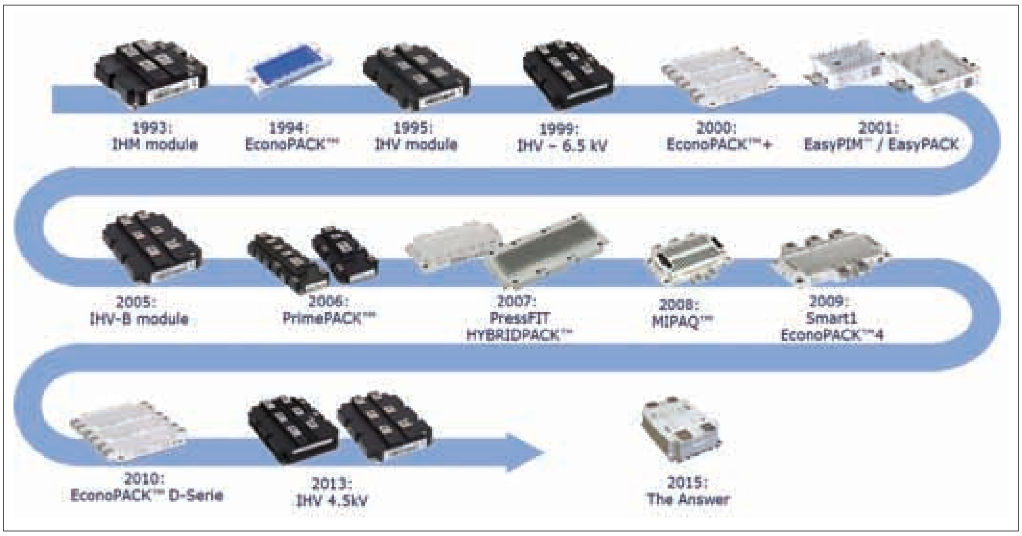


Figure 2: The new IGBT high-power package

In power modules, new applications lead to new performance requirements in four principal areas; power density, efficiency, lifetime durability and reliability. Flexibility to accommodate the need for "custom" solutions in some industries is increasingly important. In addition, constant improvement in power chip performance and anticipated adoption of innovative technologies mean that commonly used modules will ultimately fall short of market requirements. New packaging technology and a corresponding change in the form factor will address these new demands.

Infineon discussed its roadmap for high-power modules at the PCIM Europe 2014 conference. Subsequently, plans for royalty-

Figure 1: Evolution of Infineon's power module family from the year 1993 to 2015



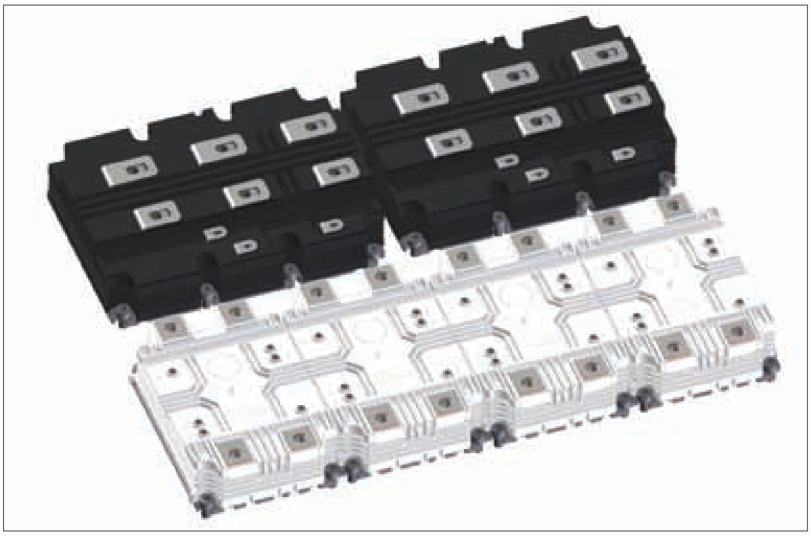


Figure 3: **Package comparison of a phase leg built of two single IHV or four dual modules**

free licensing of the new packaging and the timetable for launch of the first two platforms to use the design were announced. Here the company presents a deeper insight into the future of flexible high-power modules.

Scalability and reliability as main challenges

The new housing for high-power IGBT modules is designed to cover the full-voltage range of IGBT chips from 1.2 to 6.5 kV. Principle applications of the new package are expected in industrial drives, traction, renewable energy and power transmission. One key innovation is its scalability, which will greatly simplify system design and manufacturing. Additionally, due to its robust architecture, the new high-power platform will provide long-term reliability in applications with demanding environmental conditions.

A main focus in development of the new platform was to achieve the flexibility and reliability while assuring optimal integration into customer systems. Features defined to meet this goal include:

- Modular approach, wide scalability with high-current density
- Half bridge switch configuration, resulting in the first half bridge modules for 4.5 kV and 6.5 kV
- 1.2 kV up to 3.3 kV in a low-voltage (LV) package, 3.3kV up to 6.5kV in a high-voltage (HV) package, each one is optimized for the specific needs of this voltage range
- Design for lowest stray inductance of internal connections, which enables low inductive external connections at the same time
- Ultrasonic welding connections of highest reliability and quality
- 1.2 kV and 1.7 kV modules will be first to use new chip and joining technology.

The flexible paralleling concept allows to replace a multitude of different housings. For example, a high-voltage module portfolio of dual and single switches that is delivered today with modules of 73 x 140 mm, 130 x 140 mm and 140 x 190 mm foot prints can be reduced to one device per voltage class used in multiple parallel configurations.

Two housings with different heights are planned. The LV module with up to 6 kV insulation and corresponding creepage distances will house 1.2 kV and up to 3.3 kV chips. Two extra AC terminals will allow for the higher achievable currents of these voltage classes. The HV module, housing 3.3 kV, 4.5 kV and 6.5 kV chips, will offer up to 10.4 kV insulation and corresponding creepage distances.

These module dimensions were chosen to deliver a footprint similar to currently used IHV-A and IHV-B modules. Due to the unchanged depth of 140 mm, identical extruded heat sink profiles can be used. Four modules with a foot print of 140 mm x100 mm, mounted without a gap due to an alignment hook, will fit exactly into the space used today by two 140 mm x190 mm IHV modules, with a mounting space, to build one phase leg. The achieved current density for this configuration of four paralleled devices is 14 % greater than a phase leg with the same footprint formed by two IHV modules using the same chip technology. Figure 2 shows the new IGBT high-power package.

Figure 3 shows the package comparison

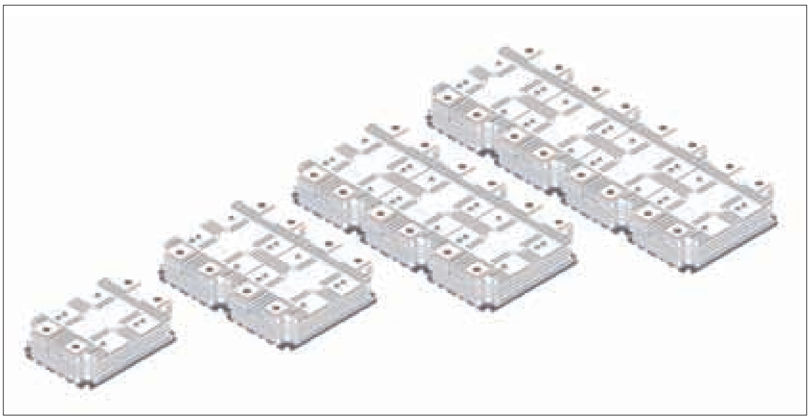


Figure 4: **Scalability by simple paralleling**

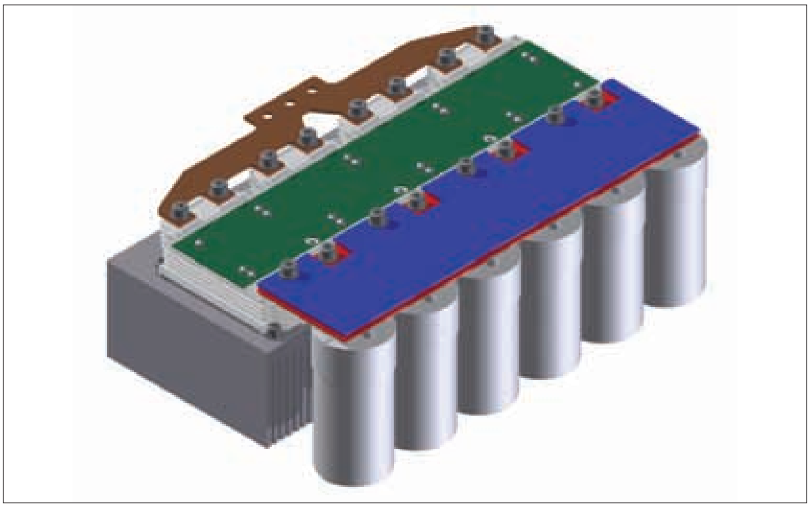


Figure 5: **Four new high-power modules in parallel with gate PCB, DC-link and phase output busbar**

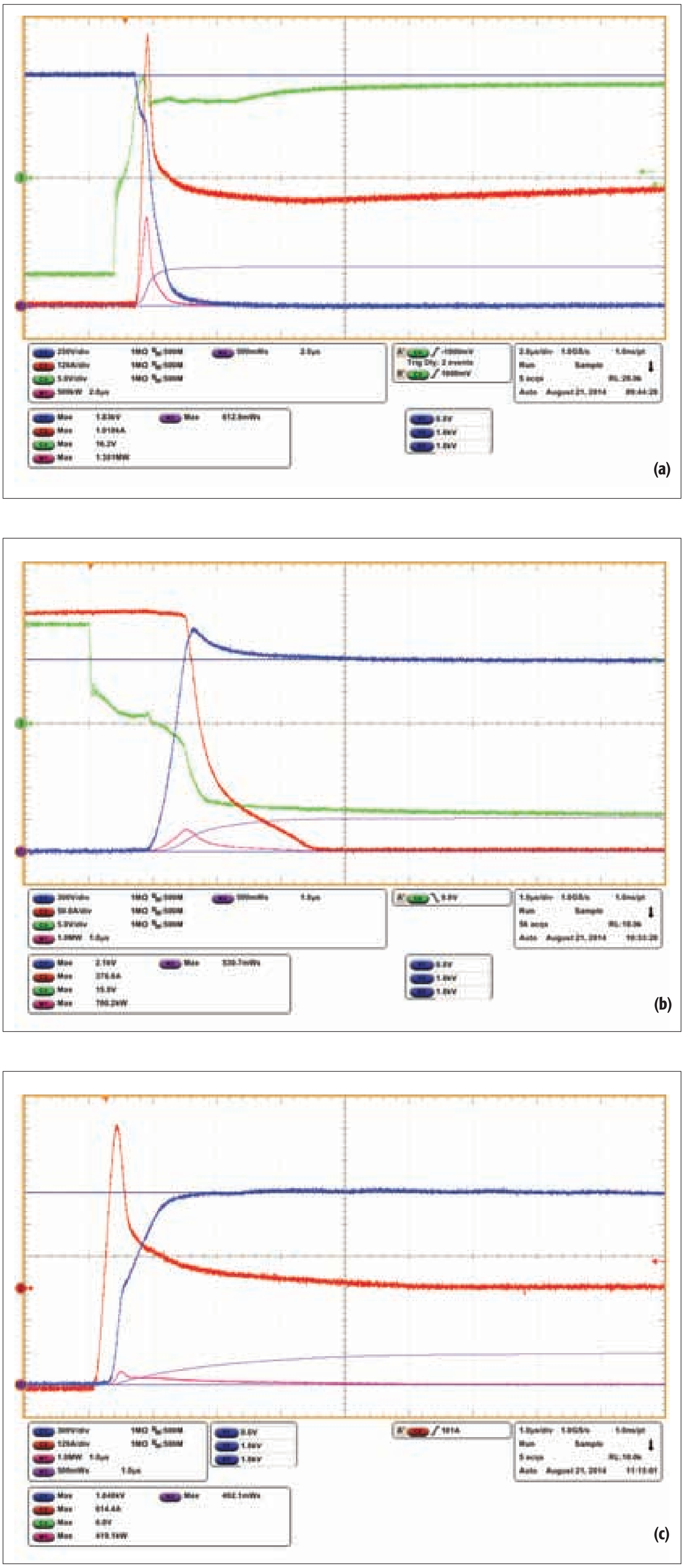


Figure 6: **Switching waveforms of FF450R33TE3 for turn-on (a), turn-off (b) and recovery (c) at nominal conditions 1800 V / 125°C**

of a phase leg built of two single IHV or four dual modules. This example illustrates how, in comparison to existing products, the modular approach of this packaging leads to considerable flexibility. This concept makes it possible to easily parallel the high-power platform for various applications; the single module is simply a building block for units with higher current ratings. Paralleling of up to four devices will not need a derating from user side due to an excellent internal and external current sharing.

The terminal arrangement also allows an easy-to-implement "flow through concept". The DC-link terminals offer a simply structured connection to the capacitor bank and the AC terminals can be paralleled by a single bar. The area in between can be used for an interconnecting PCB carrying driver or the booster stages. In Figure 4 scalability by simple paralleling is shown.

Due to a commutation inductance between the upper and lower switch of less than 25 nH for the HV module, in combination with the easy-to-implement "flow through concept," the new platform allows for low stray inductance of the overall commutation loop. In Figure 5 four new high-power modules in parallel with gate PCB, DC-link and phase output busbar are shown. In Figure 6 switching waveforms for turn-on (a), turn-off (b) and recovery (c) of the first product, the FF450R33TE3, are shown.

Conclusion

Infineon is building on more than two decades of leadership to again provide a new platform for implementation of high-voltage power systems. "The Answer" we have developed to problems faced by industrial customers provides fundamental benefits that extend from today's state-of-the-art to future new technologies. Users can expect a scalable product range based on a single platform product for the LV and HV range across flexible frame sizes, delivering reduced system and life cycle costs; support for the latest chip technologies, such as RCDC and wide-band gap for highest power density; and suitability for the latest joining technologies, delivering highest reliability and long lifetime. To make the benefits of the new module broadly available, Infineon is offering a royalty-free license of the design to all providers of IGBT power modules. First products using the platform concept will include the high voltage classes 3.3 kV (450A), 4.5 kV (400A), and 6.5 kV (275 A) with the newly designed package measuring 100 mm x 140 mm x 40 mm.

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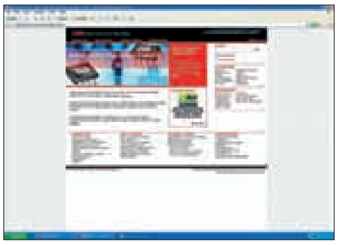

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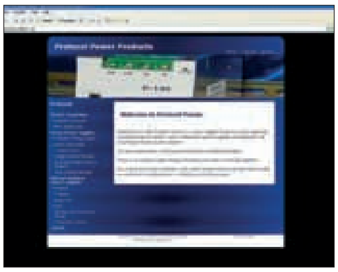

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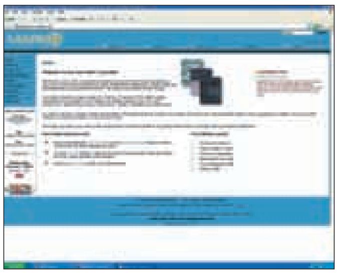

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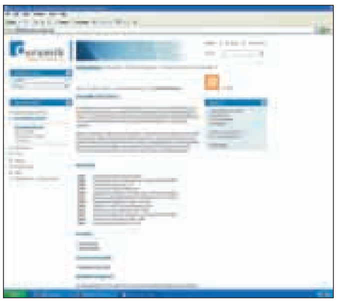

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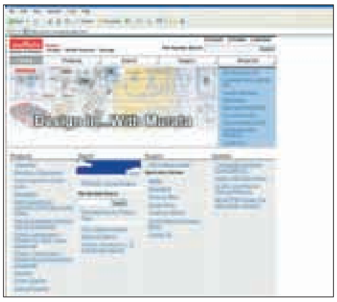

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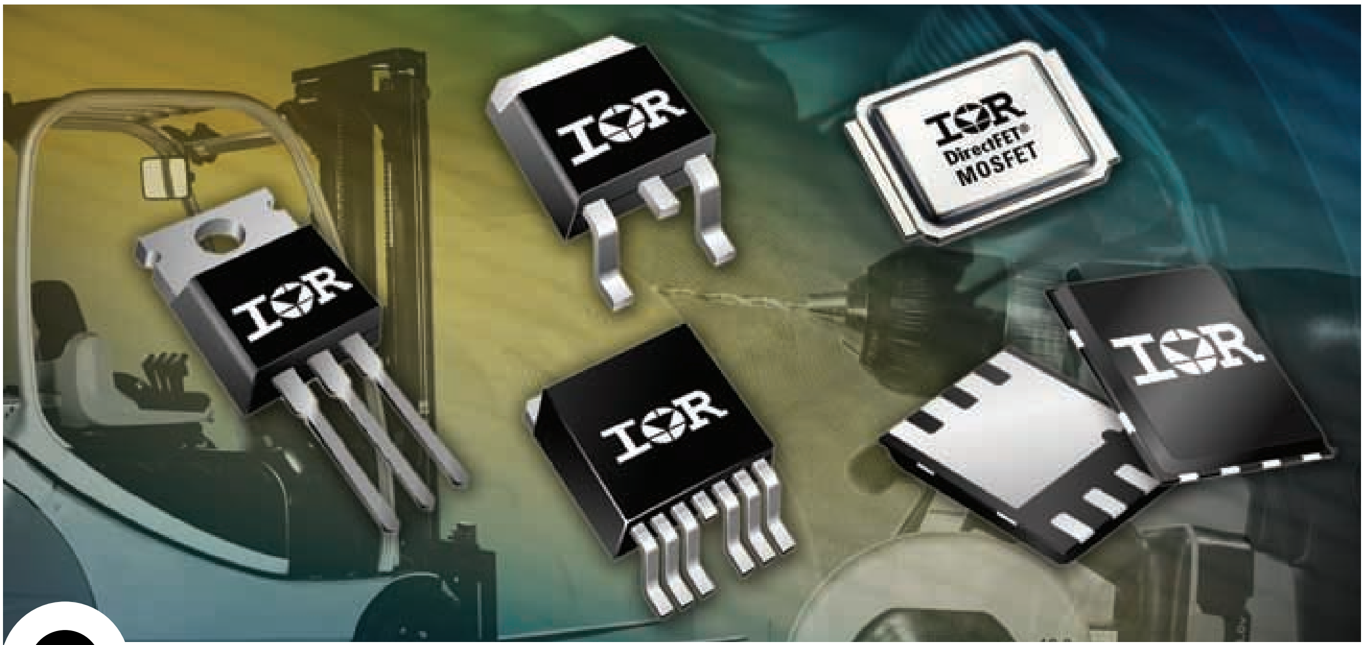

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	25	100	1.05	52	IRFH8202TRPbF
	30	100	1.1	58	IRFH8303TRPbF
	30	100	1.3	50	IRFH8307TRPbF
	40	100	1.4	134	IRFH7004TRPbF
	40	85	2.4	92	IRFH7440TRPbF
	40	85	3.3	65	IRFH7446TRPbF
DirectFET Med.Can	30	192	1.3	51	IRF8301MTRPbF
	40	90	1.4	141	IRF7946TRPbF
	60	114	3.6	120	IRF7580MTRPBF
D²-Pak	40	195	1.8	150	IRFS7437TRLPbF
	40	120	2.8	90	IRFS7440TRLPbF
	60	120	5.34	86	IRFS7540TRLPbF
D²-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
	60	195	2.0	274	IRFB7530PbF
TO-247	40	195	1.3	300	IRFP7430PbF

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