POWER ELECTRONICS EUROPE

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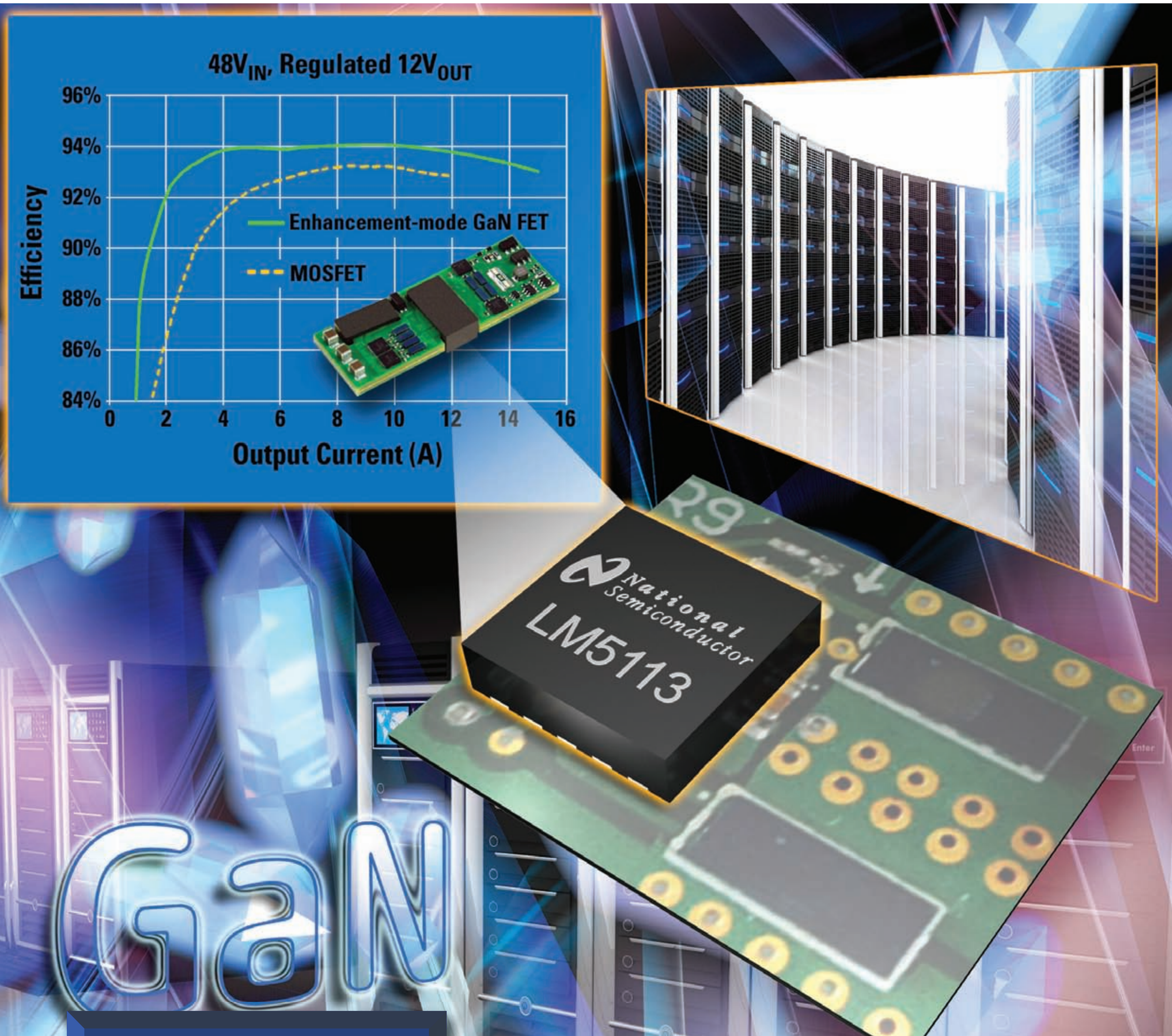
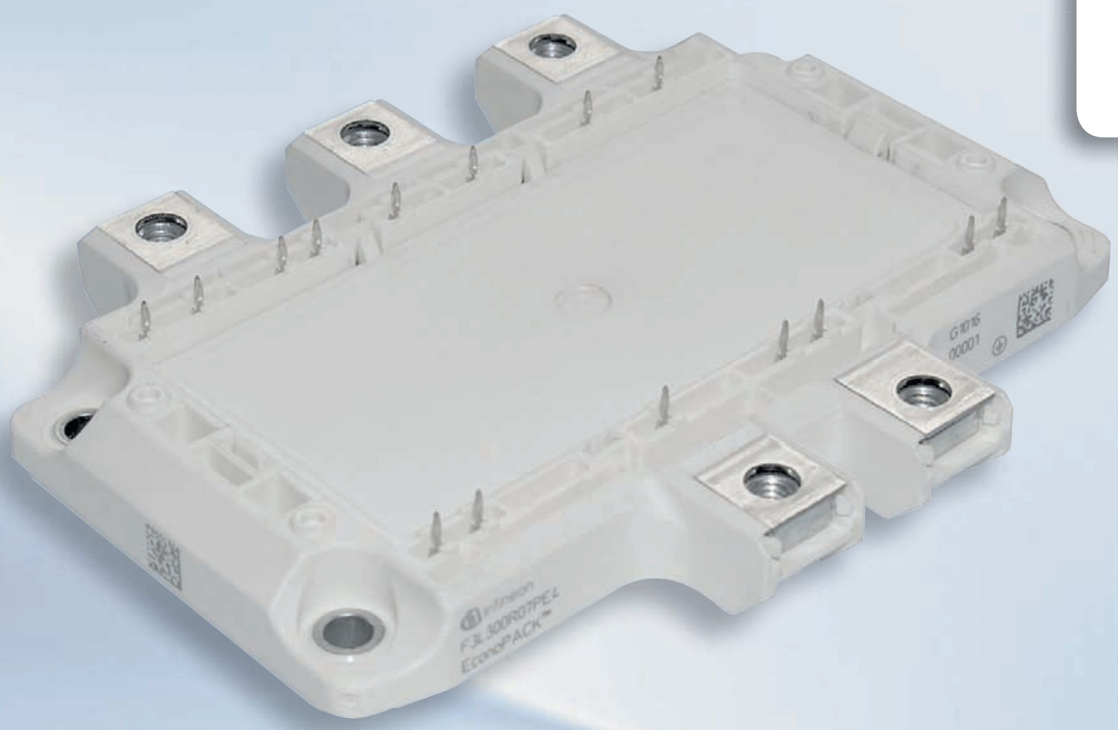
POWER SEMICONDUCTORS

The GaN Opportunity - Higher Performances and New Challenges



Also inside this issue

THE EUROPEAN JOURNAL FOR POWER ELECTRONICS AND TECHNOLOGY



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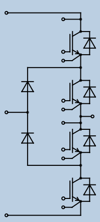
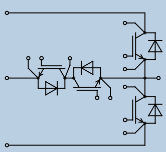
- Optimized for $f_{sw} \geq$12kHz
- Portfolio
  - F3L200R07PE4
  - F3L300R07PE4



NPC2 topology

- 650V/1200V IGBT4
- Optimized for $f_{sw} <$12kHz
- Portfolio:
  - F3L300R12PT4_B26
  - F3L400R12PT4_B26



[www.infineon.com/highpower]

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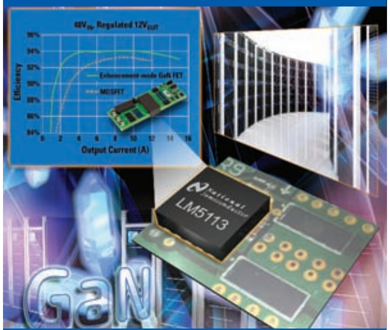
COVER STORY



The GaN Opportunity - Higher Performances and New Challenges

The recent and rapid research on wide-bandgap III-nitride semiconductor devices driven by LED, RF power stage, radar, and aerospace enabled the introduction of GaN power FETs, which are able to provide a relevant power density and thermal characteristics improvements over standard Silicon MOSFETs. This new class of devices, with best in class on-resistance and gate charge, exhibits excellent figure of merit (FOM), high frequency operation and small package footprint, represent the best choice in power converters in which efficiency and power density are a concern. Although these devices can be extremely useful in industrial power electronics applications and improve the efficiency and the regulation of AC/DC and DC/DC converters, they do not come free of challenges.

This article will briefly cover the main features of GaN FETs for power application to really understand trade-offs between the potential benefit achievable with this new disruptive technology and its new class of issues; the central part of the article will emphasize the problem relating to GaN gate driving and it will then conclude introducing the LM5113, which represents the first available driver specifically designed for GaN FETs.

Full story on page 19

Cover supplied by National Semiconductor

Growing Markets for Power Semiconductors

Though Europe and in particular Germany currently faces a financial crisis on the stock markets due to huge debt in some countries of the European Union, the power electronic market is still healthy. Hopefully we will not see a similar downturn occurred in 2008/2009 as a result of the banking/mortgage disaster mainly in the US.

Although doubts and worries persist on the state of the world economy, the semiconductor industry is performing well against all odds, iSuppli observed, even on a quarterly basis. For instance, revenue in the first quarter this year declined only 1.4 percent compared to the fourth quarter of 2010. This represented the smallest sequential decrease since 2006 during what is normally the slowest season of the year for chip sales. Sequential growth is anticipated to return for the rest of the year, with revenue rising by 2.9 percent in the second quarter and by 7.4 percent in the third. The fastest-growing semiconductor product segments in 2011 will be image sensors, NAND flash memory, light-emitting diodes, microprocessors, discrete components, sensors and general-purpose analog integrated circuits. Collective revenue from these products is projected to rise by more than 12 percent in 2011, with CMOS image sensors leading all products with 36 percent growth.

Following the 2009 slump, the power semiconductor discrete and module market bounced back and grew by 43 percent in 2010 due to a year of spectacular recovery. The market grew to just under $16 billion in 2010, almost $2 billion higher than its 2008 peak. The main drivers of growth were industrial motor drives, automotive and computer & office equipment. These applications have one thing in common: the adoption of the latest devices to improve power conversion efficiency. The power module market grew by 65 percent in 2010, significantly faster than discrete power semiconductors. This was fuelled by the recovering industrial motor drive market and a rapid expansion of inverter production for renewable energy applications. IGBT module sales boomed on the back of a wave of industrial motor drive installations in new factories, the construction of which had been delayed by the recession. Sales of power modules in renewable energy inverters grew by a staggering 98% as countries rushed to install solar PV systems.

In 2011 US PV installations will rise a spectacular 166 percent to a total of 2.4 GW, with California leading the country in the amount of power derived from renewable solar energy, according to iSuppli. The number of US PV installations this year is projected to climb to approximately 49,000 - up from 39,000 in 2010. Of the 2.4 GW in solar power expected to be installed this year, ground installations will contribute approximately 1.4 GW, commercial installations 710 MW and residential installations 270 MW. Next year, new solar installations will reach an estimated 3.1 GW, on the way to some 5.5 GW by 2015. And while a downturn next year is forecast for Europe, growth will be good stateside because of healthy support from the US Department of Energy in the form of loan guarantees to help stimulate the market and help secure a lower cost of capital for large projects.

According to IMS Research, several European markets, including Germany are predicted for a major slowdown or even a fall in 2011. However, Europe overall will be only 1 percent down this year due to geographic diversification, with high demand coming from a number of new countries such as Slovakia and the UK. 11 countries in Europe will install at least 100 MW this year, with 20 countries globally installing this amount or more - up from just 13 the previous year. This increasing diversity in the market is helping to support demand and provide stability to a market that was once dependent for growth on just one or two countries. One significant factor is the recently introduced national FIT in China which was revealed by the NDRC this week. This FIT pays a premium for installations completed this year, but continues past the end of the year and is in addition to the country's Golden Sun scheme. Installations of 1.3 GW are forecasted this year and more than 2 GW in 2012. In the longer-term, IMS Research projects that China will become a key player for PV and not just for production, with it becoming one of the top three global markets in 2015. Although Europe still dominates the global PV market, only four of the 10 most important markets in 2011 will be European, with Asian markets ranking prominently. At the same time, it's important to remember that Europe will still account for close to 70 percent of global installations this year and in fact the next five largest markets are all European, IMS underlines.

Hopefully, these actual research results are valid for a longer period of time and thus demand for power semis will still be high in the mid-term.

Achim Scharf
PEE Editor

Lithium-Ion Battery Market Set for Boom

Driven by plunging prices and accelerating demand from the electric and hybrid automobile market, lithium-ion will emerge as the world's leading rechargeable battery technology and achieve 350 percent revenue growth from 2010 to 2020, according to a new IHS iSuppli Rechargeable Batteries Special Report.

Global lithium-ion battery revenue is expected to expand to $53.7 billion in 2020, up from $11.8 billion in 2010. Revenue will rise to $31.4 billion in 2015, allowing lithium-ion to surpass the current dominant rechargeable battery technology, lead acid.

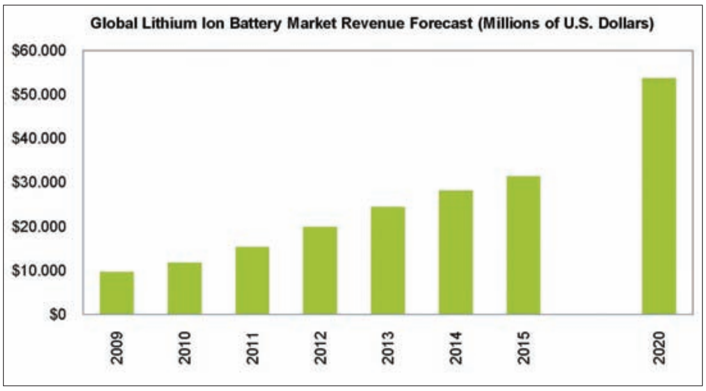
While lithium-ion will find wide usage in mobile electronics products such as cellphones and notebook PCs, usage in cars will fuel the bulk of sales growth. "Lithium-ion at present is much more expensive than alternative technologies, costing two to three times as much as sodium-sulfur, lead-acid and nickel-metal-hydride rechargeable batteries," said Satoru Oyama, principal analyst of Japan electronics research for IHS. "However, lithium-ion pricing will decline much more rapidly than the other technologies, coming close to cost parity in 2015, and then becoming the least expensive type of rechargeable battery in 2020. Combined with the inherent advantages of the technology, the increasingly competitive cost of lithium-ion will cause car makers to employ it as their battery technology of choice in future electric and hybrid vehicles."

Lithium-ion delivers several enhancements compared to other rechargeable battery technologies. These advantages include more flexible form factors and lighter weight. Furthermore, lithium-ion devices have no memory effect, meaning they maintain their full capacity even after a partial recharge. Finally, lithium-ion batteries are considered to be more environmentally safe than other technologies. These features make lithium-ion particularly attractive for electric vehicles, hybrid electric vehicles and plug-in hybrid electric vehicles. Because of this, the automotive segment will be the leading market for lithium-ion batteries by 2015, surpassing the current top application, notebook PCs.

Lithium's elements of success in hybrid and electric vehicles

The dominant battery technology used in hybrid cars now is nickel-metal-hydride. More than 1 million hybrids with nickel-metal-hydride batteries were shipped in 2010, led by the Toyota Prius. However, shipments of nickel-metal-hydride batteries to the HEV market will not grow in the future as the use of lithium-ion begins to take off.

One concern regarding the use of first-generation lithium-ion batteries in cars is safety. There can be a risk of fire using existing lithium-ion battery materials due to the high temperatures involved. There have been documented incidents of lithium-ion battery fires in smaller devices, such as PCs and mobile phones. To achieve acceptable safety levels for hybrid and electric vehicle batteries, lithium-ion battery makers must take steps to prevent internal short circuits which can cause external damage. These steps include improving control of power generation during discharges and enhancing the management of rapid charging.



While automotive will be the dominant market for lithium-ion batteries, notebook PCs and cellphones will remain major markets for the technology, accounting for $12.3 billion in revenue in 2010, up from $7.8 billion in 2010. Other major uses for lithium-ion batteries include use in solar power systems, smart electricity grids and electric tools.

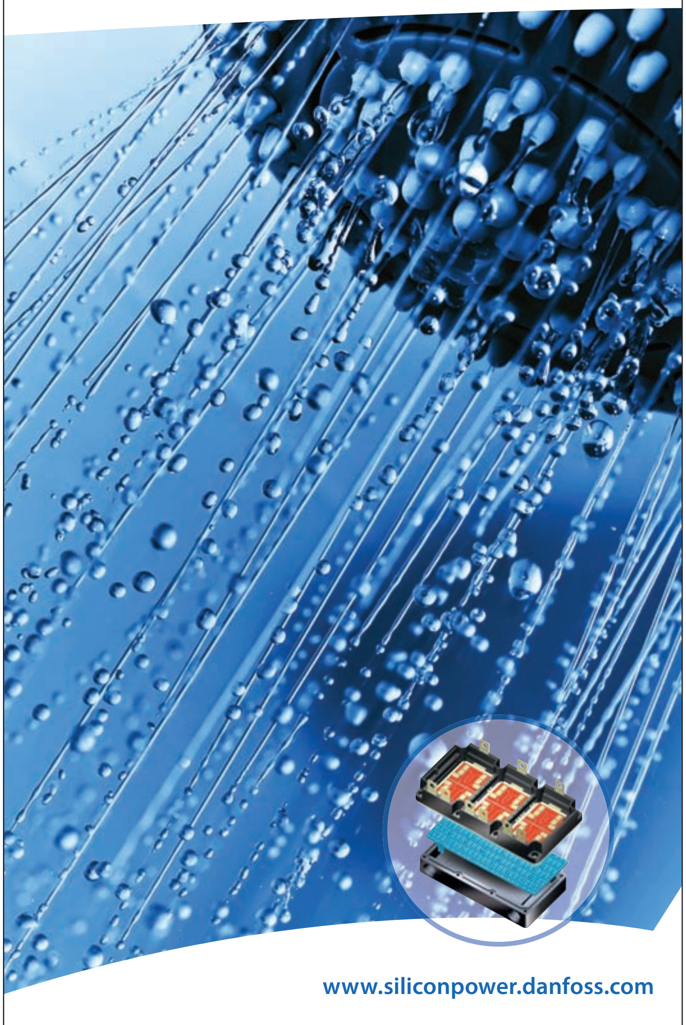
www.ihs.com

Semikron's Power Electronics Knowledge Platform Goes Online

The new knowledge platform provides basic information on semiconductor physics and power electronics, as well as detailed information on IGBT, MOSFET, diode and thyristor component selection and applications. The knowledge platform is to facilitate and make more efficient the work of development engineers.

The power electronics knowledge platform aims at both professional development engineers and professors and students of relevant subject areas. Besides containing examples of field applications and first-rate papers on technologies and innovations, this platform represents an endless knowledge base that draws upon many years of engineering experience and development expertise. Users can also post comments on a variety of subject areas, participate in online discussions, and subscribe to the latest chapters, e.g. by RSS feed. Five publications dealing with power electronic basics will initially go online, with more articles being published at regular intervals. In addition, the knowledge platform will be continually improved on with additional new features and functions. "The printed version of our application manual opens up the doors to a vast knowledge base that draws upon a wealth of expertise and years of field experience. Now, this vast knowledge base is being opened up to interested parties online," stated Gerlinde Stark, Head of International Communication.

www.powerelectronics-base.com



Nexeon Scales up Battery Production Capacity

Rechargeable lithium-ion battery technology has received a huge boost with the investment of £40 million in UK-based Nexeon, the company pioneering the use of Silicon anodes in place of Carbon.

Nexeon plans to use the new funding to establish a world class manufacturing facility, scaling up the production of its latest silicon anode materials to around 250 tonnes per annum, representing a commercial supply level. "Use of Silicon anodes in Li-ion batteries produces a significantly higher performance and overcomes the limitations of present-day technology. Batteries with higher energy density can offer longer time between charges, higher power output, smaller size or a combination of these benefits. They are eagerly awaited for application in cell phones, laptops and many other consumer devices, as well as having important application in electric vehicles and in storage of renewable energy," says Nexeon Chairman Paul Atherton, who founded the company back in 2005 with Professor Mino Green of Imperial College. "It's a superb example of UK high value manufacturing involving sophisticated advanced materials, and this funding will enable Nexeon to establish the first in a series of manufacturing plants that will be needed to serve demand worldwide."

www.nexeon.co.uk

Electric Cars are Suitable for Everyday Use

Electric cars are an excellent choice for everyday use, in particular for daily trips in the city. This conclusion is the result of user analyses in two projects in which Siemens played a decisive role.

The internal 4-Sustain electromobility (4-S) project involved 20 moveE cars and the external "Electromobility Model RegionMunich - Drive eCharged" project involved 40 BMW MINI E cars. The latter is a joint project with BMW Group and Stadtwerke München, Munich's municipal utility.

The majority of users confirmed that the BMW MINI E is suitable for everyday use. They attested to the fact that the little 200-HP electric speedster is a lot of fun to drive. Private and commercial users drove 40 MINI E cars on Munich streets over a period of ten months. During the model trial the electric vehicles were driven 300,000 kilometers, with zero emissions. Siemens developed the technology for charging.

The scientific survey revealed that the range of the MINI E was sufficient for 89 percent of the private users in day-to-day use. 88 percent of the private users found charging the cars at a charging station (at home or at work) to be more pleasant than driving to a gas station, while 79 percent of the private users said that environmental friendliness and zero-emission driving were important advantages of the electric car. And 59 percent of the private users would like electric cars to be charged exclusively with electricity from renewable energy sources.

The test drivers of the movE cars had similar positive experiences. In the 4-S project, funded by the German Ministry for the Environment, Siemens employees in Munich and Erlangen have been testing 20 electric cars based on the Suzuki Splash since November 2010. On weekdays, the test drivers drove an average of only 40 kilometers, which means that the range of approximately 100 kilometers was fully adequate. The cars are charged at charging stations in specially marked parking lots at the Siemens locations where the test drivers work and at home charging stations in their garages (so-called wall boxes).

Thus, the drivers usually have sufficient opportunity to recharge the batteries during the day. The usage as second cars for driving to work or for shopping imposes almost no restrictions on mobility. In the meantime the electric cars were equipped with high-speed charging systems (11 kW), meaning that the batteries can now be charged within two hours.

www.siemens.com/innovationnews

Power-One License on Digital Power for ZMDI

Dresden-based ZDMI (Zentrum Mikroelektronik) have entered an agreement for Digital Power Technology (DPT) patents from Power-One. As applications in server, storage, networking and wireless infrastructure continue to drive board densities higher, requiring complex power architectures to drive FPGAs, ASICS, DSPs and other semiconductor devices, Digital Power Technology is an attractive solution.

Digital Power Technology drives increased system efficiency, improved design flexibility, faster time to market, decreased footprint size and lower system costs. DPT also enables telemetry capability, providing access to critical information including current, temperature and voltage. Telemetry allows the system to accurately monitor its power consumption and thermal performance, enabling designers to easily engineer key features such as system optimization, fault detection and predictive maintenance features into their end products. “Leveraging the DPT patents meshes with our goal of delivering energy-efficient solutions for point-of-load applications,” stated Bernhard Huber, ZMDI Business-Line Manager for Standard Components. “We can focus on developing chipsets that address all output loading conditions based on ZMDI’s performance goals.” ZMDI has 280 employees worldwide.

www.zmdi.com

Fourth Patent for CogniPower Technology

CogniPower announced the issuance of its fourth patent (# 7965064, Power Conversion Regulator with Predictive Energy Balancing). Coupled with already issued patent # 7492221, these cover the fundamental principals for control of power converters based on predictive energy balancing.

According to Thomas Lawson, Founder and President, “Predictive energy balancing solves the most persistent control issues dogging switch-mode power converters regarding the necessary trade-offs between stability and agility. Predictive power converters can be both remarkably agile and exceptionally stable. One predictive power converter can replace two regular power converters, cutting power losses by half. At the same time, predictive power converters afford an opportunity to drastically reduce both size and cost.”

www.cognipower.com

Renewable Energies Push LEM Forward

For the full fiscal year 2010/11, Geneva-based LEM reports strong results driven by a substantial volume increase combined with the efficient cost management program initiated during the financial crisis. Also François Gabella has served for one year as CEO of LEM Holding SA, an opportunity for PEE to speak with him about the markets LEM serves and future prospects.

PEE: Mr. Gabella, you were appointed as LEM CEO approximately one year ago. LEM is concentrating on current transducers for various applications and power ranges. Obviously you had a good start with sales increased by more than 70% up to CHF 296 million in fiscal year 2010/11. This is in line with power semiconductors which have also grown significantly in 2010 due to recovery from the crisis in 2009. They are forecast to grow by 10% this year, driven by various growing application segments. Will the transducer market grow as fast or even faster?

In 2010 in power electronics the usage rate has been increased by around 20 percent by jumping out of the crisis. There has been a shortage in components and some customers ordered slightly more than they needed and more in advance, explaining this higher rate of growth. We expect a more moderate growth in 2011.

PEE: Most of the applications for power semiconductors including power modules are focused on renewable energies. Particularly the Japanese nuclear crisis has given a push for solar and wind energy generation worldwide - especially here in Germany by the decision to step out of nuclear power. Do you expect a major push for your business from this possible transition?

We have benefited from the high growth in power semiconductors and also from the fast growth in the renewable energies. However, I see a market correction in this segment that took place already earlier this year and before. Now, in face of the nuclear crisis in Japan and the political consequences in other countries I see promising opportunities for our industry because governments like Germany or Italy were very quick to push the stop button for existing and future nuclear power plants. Therefore, the mentioned market correction of the renewables will be offset and they will grow progressively before the end of this year, though there will be a market consolidation among the tremendous amount of players. We are working hard in developing innovative solutions for renewables.

François Gabella has served for one year as CEO of LEM Holding SA, sales increased by more than 70% up to CHF 296 million in this time

PEE: Which segment is more interesting for LEM - solar or wind power - the latter with its higher power range?

We are addressing all installation sizes, from the smallest solar to the biggest wind power applications. Wind is much closer to our traditional drive business,

PEE: With renewables - its not only the generation, but also the transmission & distribution and storage of electrical energy which requires a lot of conversion stages. In other words the Smart Grid, what do you expect from this technology in the mid-term in general and for your business in particular?

In contrast to the traditional centralized power stations with its uni-directional power distribution these networks will have to be much more complicated because power generation will be intermittend and power flow will be bi-directional. This requires also a lot of current measurement equipment including smart meters. We have our fingers in this market segment.

PEE: Also related with Smart Grids are Electric Vehicles (also for electrical energy storage applications). Here additionally management of the HV Li-Ion battery comes into play, that's also a business opportunity for LEM since the company is well established in battery management for automotive and large UPS installations. What is your expectation of this evolving market in the long-term?

We have been in the automotive business for ten years and thus have very good contacts to major manufacturers. For conventional cars we provide battery management systems, the technology needed for "greener cars" is more demanding due to the higher voltage and cell balancing, and there is still some uncertainty about the appropriate technology. But we are already designed in to more than 70 percent of conceptual or actual series cars. The high content of current transducers is very important for us, not only in battery management but also in the electrical drives. We are in the starting blocks ready for this market to move, but the question mark is, when this market goes up because of the relatively high price of green cars and possible incentives in pushing the market. We are also working with the manufacturers of charging stations where accurate current measurement is a must.

PEE: Speaking about transducer technologies - LEM is well known in Hall-effect open/closed loop and flux gate sensors, what comes next and what is your opinion about high-precision shunts in your opinion?

The Hall-effect and flux gate transducers have always been in competition with other technologies. This battlefield is based on the relation between performance, mainly precision versus cost. We are working on making our offer more competitive and investing in penetrating applications that traditionally have not been served by transducers.

We spend more than five percent of our revenues in R&D in order to reach our objectives.

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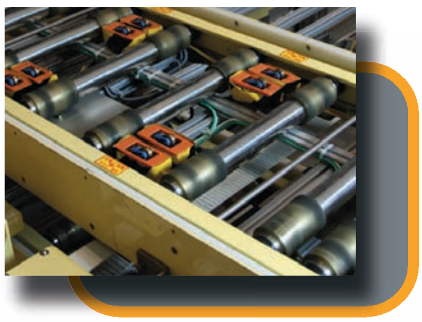

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		1600A	●	●	
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		1500A			●
		2400A	●	●	
		3600A	●	●	
2-Pack	 130 x 140 mm	600A	●	●	
		800A	●	●	
		1200A	●	●	
	 89 x 172 mm	600A	●		
		650A		●	
		900A	●		
	 89 x 250 mm	1000A		●	
		1400A	●	●	

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LED Lighting Driver ICs Reached $160m in 2010

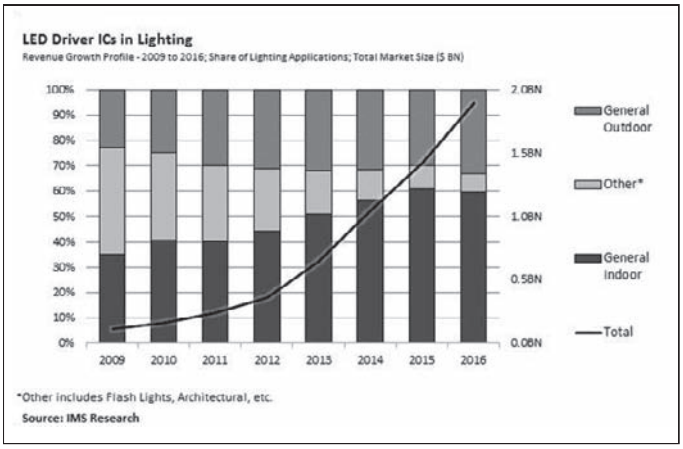
Accounting for 16% of a $1 billion LED driver IC industry in 2010, ICs for lighting applications are expected to be worth 55 % of a $3.5 billion market in 2016. According to IMS Research, residential lighting was the second largest lighting segment after street/parking lighting in 2010. Overall, indoor lighting (including office and commercial) will lead the growth in the lighting area.

Within lighting, there is also a focus on LED retrofit bulbs. They are considered direct replacements for incandescent bulbs, which are being progressively banned across the world. LED prices are currently hindering adoption. However, lower costs, higher efficiencies, government subsidies and a healthy LED oversupply will result in significant price reductions which will boost demand. By 2016, it is expected that LED retrofit bulbs will account for the clear majority of all LED driver ICs in lighting.

Although two of the largest suppliers in this industry are set to combine and represent nearly a quarter of all LED driver ICs revenue, general lighting focused suppliers are making good traction in the supplier share rankings. "Companies such as NXP, Power Integrations, ST Micro, ON Semi, Diodes, and Texas Instruments were some of the strongest suppliers in lighting in 2010," said Mitess Nandha, LED driver ICs analyst at IMS Research. "Most LED driver ICs suppliers now agree that this lighting market will be huge and new products are continually coming to market. In the coming years, this shift to LED lighting could cause a continued shake up of the leading suppliers."

Although set to be overshadowed by general illumination, backlighting will remain a significant portion of this market. LED backlit TVs, monitors and notebooks have surged in the past year and are showing signs of continuing strong growth until 2013. "TVs accounted for 25 percent of LEDs revenue in 2010 compared to only nine percent of LED driver ICs revenue as the ratio of LEDs to LED driver ICs here is generally very high," Mitess added. "Typically 5 to 1 or 10 to 1 at the moment for an indoor lighting application, compared to 100 or 1000 to 1 in a TV."

www.imsresearch.com



CISSOID Joins Center for Power Electronics Systems

Belgium-based CISSOID joined the Center for Power Electronics Systems (CPES) as an affiliate member. CPES is a $4 million/year research center within Virginia Tech (USA). CPES is dedicated to improving electrical power processing and distribution that impact systems of all sizes - from battery-operated electronics and vehicles to electrical distribution systems.

CISSOID will support CPES research in high-temperature power module and power converter designs. The company will be bring its upcoming solution HADES®, a complete 1-leg isolated gate driver dedicated to Silicon Carbide (SiC) switches and other wide-bandgap semiconductor power devices. HADES will be based on CISSOID's most recent integrated implementation of the gate drive, the isolated transceiver and the switched power supply functions. The TITAN chipset is a solution for new generation of power converters, motor drives and high power density modules. CISSOID is delivering standard products and custom solutions for power management, power conversion and signal conditioning in extreme temperature and harsh environments.

www.cissoid.com

Compact 25 W LED Lighting Ballast Reference Design

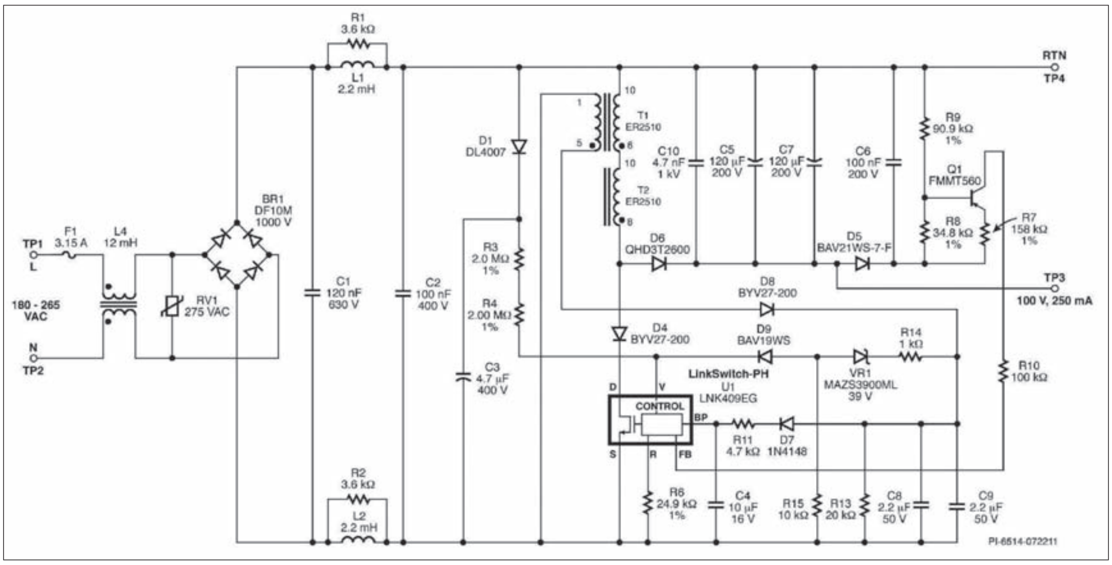
Power Integrations' LinkSwitch-PH has been developed to cost effectively implement a single-stage power factor corrected LED driver and primary-side constant-current control. The LinkSwitch-PH controller is optimized for LED driver applications and requires minimal external parts. It provides control of the output current through the LED load without the use of an optocoupler. Described is a non-isolated, power factor corrected, low THD, high-efficiency LED driver designed to drive ~100 V LED string at 250 mA from an input voltage range of 180 to 265 VAC.

The buck-boost power circuit with floating output is composed of U1 (power switch + control), output diode D6, output capacitor C5 and C7, and output inductors T1 and T2. Inductor T1 has a second winding configured in flyback configuration used to provide a bias supply to U1. Two inductors were used due to space constraints of the tube. Diode D4 was used to prevent negative voltage appearing across drain-source of U1 near the zero-crossing of the input voltage. Diode D1 and C3 detect the peak AC line voltage. The voltage across C3 along with R3 and R4 sets the input current fed into the VOLTAGE MONITOR (V) pin. This current is used by U1 to control line undervoltage (UV), overvoltage (OV), and feed-forward current which in conjunction with the FEEDBACK (FB) pin current provides a constant current to the LED load.

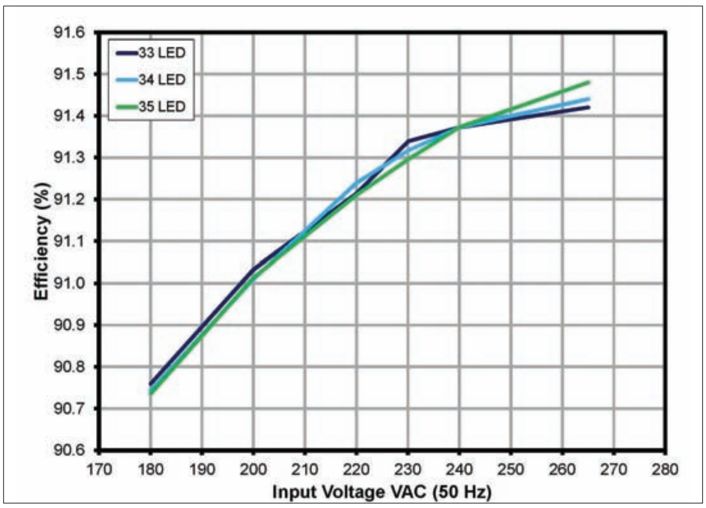
Capacitor C1, C2, differential chokes L1, and L2, plus common mode choke L4 perform EMI filtering and are sized to maintain a high-power factor. Resistor R1 and R2 are used to damp the Q of L1 and L2 to prevent a resonant peak in the EMI spectrum.

Explains Andrew Smith, product marketing manager at Power Integrations: "Achieving very high power-conversion efficiency is as critical as LED choice in maximizing overall luminous efficacy of a lighting fixture. Efficiencies above 88% are extremely difficult to achieve cost-effectively in a T8 tube form factor unless a single-stage topology is used; this design easily exceeds 91%. Most regions require either low THD or high PF in commercial and industrial lighting installations - specifications that the LinkSwitch-PH LED driver IC easily meets, enabling designs that can be used worldwide. And single-stage technology greatly increases product lifetime by eliminating the opto-isolators and large aluminum electrolytic input bulk capacitors required by conventional two-stage solutions."

www.powerint.com/linkswitch-ph



ABOVE: T8 LED string driver schematic



LEFT: Efficiency vs line and load

RIGHT: LED driver inside the T8 tube

More Enhancement Mode Gallium Nitride FETs

Efficient Power Conversion Corporation announces the EPC2012 as the newest member of second-generation enhanced performance eGaN FET family.

The EPC2012 FET is a 1.6 mm² 200 VDS device with a maximum $R_{DS(ON)}$ of 100 mΩ with 5 V applied to the gate. This eGaN FET provides significant performance advantages over the first-generation EPC1012 eGaN device. The EPC2012 has an increased pulsed current rating of 15 A (compared with 12 A for the EPC1012), is fully enhanced at a lower gate voltage, and has superior dv/dt immunity due to an improved ratio of Q_{GD}/Q_{GS}.

Compared to a state-of-the-art Silicon power MOSFET with similar on-resistance, the EPC2012 is much smaller and has many times superior switching performance. Applications that benefit from eGaN FET performance include high-speed DC/DC power supplies, point-of-load converters, class D audio amplifiers, hard-switched and high frequency circuits.

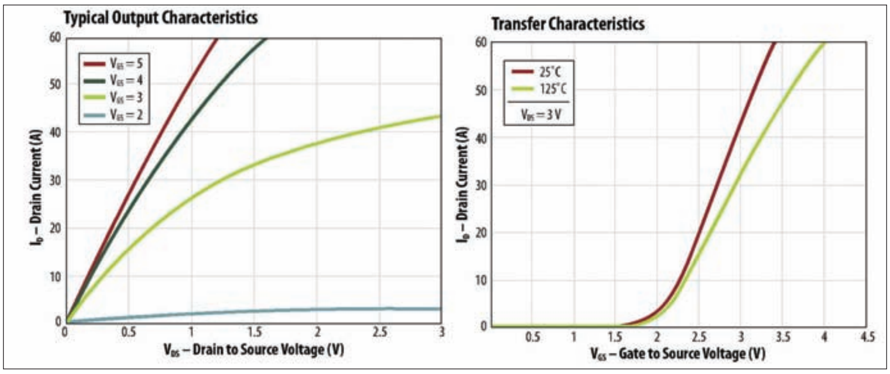
The figures on the right compare the 200 V, 3 A EPC2012 with the prior-generation EPC1012 typical output and transfer characteristics. The new generation 200 V product performs significantly better at higher currents. In addition to a higher pulsed current rating and less conduction loss at higher current, the new-generation EPC2012 has improved $R_{DS(ON)}$ at lower gate-source voltages. This allows the user to realize the low $R_{DS(ON)}$ capability of the FETs with greater margin between the applied gate voltage and the $V_{GS(MAX)}$ of 6 V. V_{GS} necessary for significant conduction current has also increased, thereby reducing turn off time and increasing dv/dt immunity. The dv/dt immunity is further improved in the second-generation EPC2010 because of the significantly improved Miller ratio. The Miller ratio ($Q_{GD}/Q_{GS(VTH)}$) has improved from a typical value of 2.3 down to a value of 1.3 for the EPC2010.

Assembly considerations

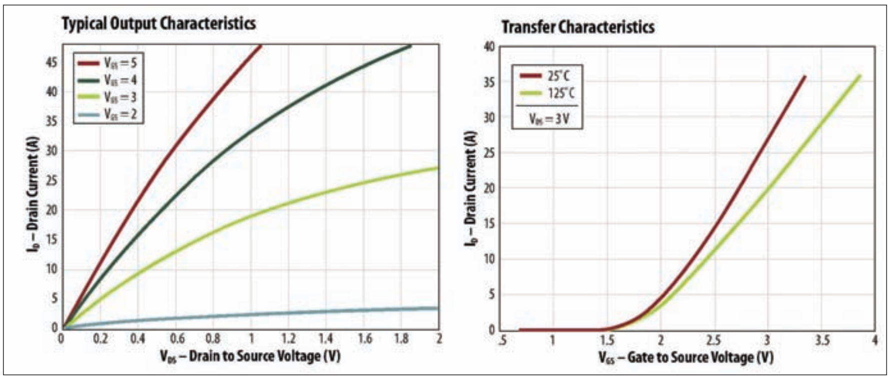
There are three physical changes to the new generation of eGaN FETs.

The first change is that there is a connection to the Silicon substrate that has been brought to the surface. It is advised that the substrate be connected to source potential to get the maximum dynamic performance from the device. The second change is the width of the solder bars. The EPC2010 and EPC2012 both have a 250 _m wide solder bar compared with 300 _m in the prior generation. The third change is that the height of the solder bars has been increased from 70 µm +/-20 to 100 µm +/- 20 for all the new generation parts. The added height allows for greater post-assembly clearance between the FET and the PCB. This clearance makes it easier to clean out foreign materials and avoids the harmful accumulation of particles.

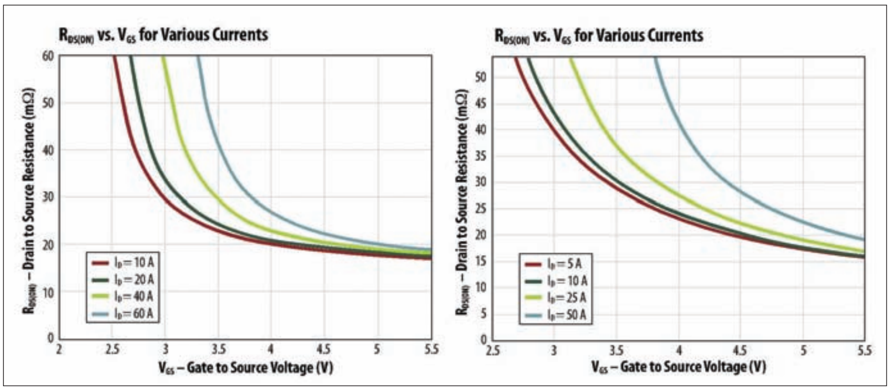
www.epc-co.com



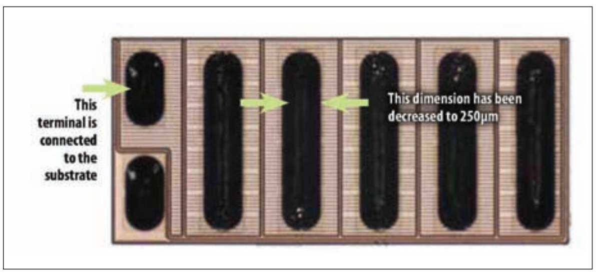
EPC2010 (RoHS) typical output and transfer characteristics. Note that the EPC2010 is rated up to 60 A pulsed



EPC1010 typical output and transfer characteristics



EPC2010 $R_{DS(ON)}$ vs V_{GS} for various current levels (left), these RoHS parts are fully enhanced at 20 A with 4 V on the gate; and EPC1010 $R_{DS(ON)}$ vs V_{GS} (right) for various current levels. These older generation parts require 5 V applied to the gate to be fully enhanced at 20 A



LEFT: Magnified die photo of EPC2010 indicating the solder bar that is connected to the Silicon substrate and the decreased solder bar width

The GaN Opportunity - Higher Performances and New Challenges

New GaN technology switches offer best in class on-resistance and gate charge, however they need more accurate driving techniques to ensure reliability and avoid overstresses and failures. This paper explains the main technical challenges and solutions to address these needs. **Maurizio Granato, Senior Circuit Design Engineer, and Roberto Massolini, Design Engineer, National's Design Center, Milan, Italy**

The recent and rapid research on wide-bandgap III-nitride semiconductor devices driven by LED, RF power stage, radar, and aerospace enabled the introduction of GaN power FETs, which are able to provide a relevant power density and thermal characteristics improvements over standard Silicon MOSFETs. This new class of devices, with best in class R_{dson} and Q_{gd}, exhibits excellent figure of merit (FOM = R_{dson} x Q_{gd}), high frequency operation and small package footprint, represent the best choice in power converters in which efficiency and power density are a concern. Although these devices can be extremely useful in industrial power electronics applications and improve the efficiency and the regulation of AC/DC and DC/DC converters, they do not come free of challenges.

This article will briefly cover the main features of GaN FETs for power application to really understand trade-offs between the potential benefit achievable with this new disruptive technology and its new class of issues; the central part of the article will emphasize the problem relating to GaN gate driving and it will then conclude introducing the LM5113, which represents the first available driver specifically designed for GaN FETs.

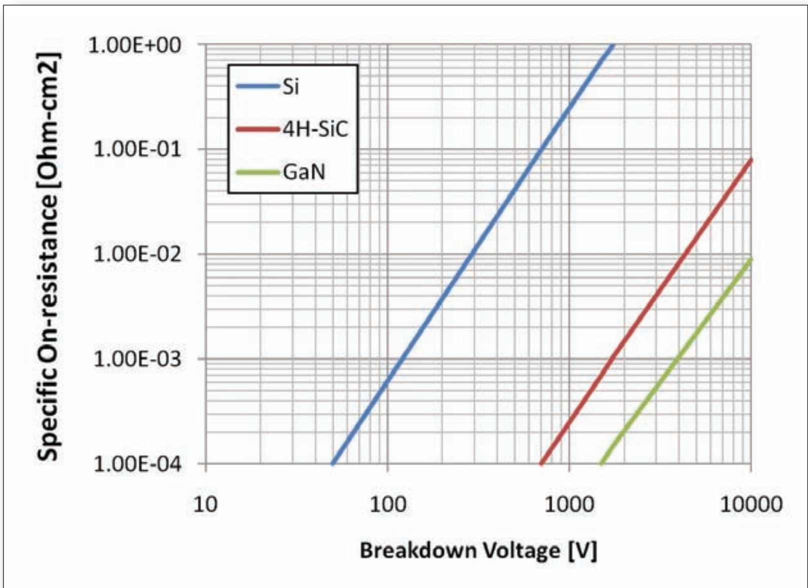


Figure 1: Technology comparison based on semiconductors physics [Naik]

GaN FETs overview

Introduced at the end of the '70s, the power MOSFETs have been transformed from mere alternatives to bipolar power transistors to the most widespread devices in the power electronics market, with the result of boosting the strong diffusion of high frequency Switch Mode Power Supplies (SMPS). The evolution of FETs has seen different technologies like TrenchFETs, HEXFETs, Superjunction and many others and provided a slow and continuous improvement in MOSFET switches performances. In recent years the cost-effectiveness of alternative materials (like GaN, SiC) has started to challenge the best Si-based devices providing a disruptive technology change.

We can compare the intrinsic performances of GaN devices to the more mature SiC technology. On one hand, GaN allows for breakdown voltages close to SiC, and twice the electron mobility (in fact, those devices are often named High Electron Mobility Transistors HEMTs); moreover the GaN industry is mature thanks to the developments in optoelectronics (wide application in LEDs) and there are already many suppliers in the market, bringing expectable price reductions compared to SiC. On the other hand, thermal conductivity of GaN is roughly 1/4 of SiC; moreover, power GaN devices development started 10 years after SiC, meaning less maturity and reliability (see Table 1)

The availability of low cost GaN devices has been enhanced by the improvement in process manufacturing techniques and by the adoption of more economic substrates. From the 2-inch very expensive GaN substrates, to the 4-inch SiC substrates, to 6-inch sapphire substrates, to recent growth on Silicon substrates (up to 12-inches), the cost reduction has been massive. On the other hand, this has required a significant effort in engineering to improve device reliability and to keep the high performances, without suffering problems from lattice and thermal expansion mismatch.

The most visible advantage in adopting GaN-based devices is a significant reduction of the on-resistance for a

Materials Property	Si	SiC-4H	GaN
Bandgap [eV]	1.1	3.2	3.4
Critical Field [10^6 V/cm]	0.3	3	3.5
Electron Mobility [cm^2/V-sec]	1450	900	2000
Electron Saturation Velocity [10^6 cm/sec]	10	22	25
Thermal Conductivity [W/cm^2 K]	1.5	5	1.3

Table 1: Comparison of intrinsic materials properties [Microsemi]

specific breakdown voltage, or, equivalently, a much higher breakdown voltage for a specific on-resistance. A reasonable expectation over the long run is that SiC based devices will achieve one order of magnitude better R_{dson} with regard to Silicon devices, and GaN based devices will provide a further 2-3x enhancement. Moreover, such a decrease in on-resistance also comes with a significant reduction of the gate charge required to turn-on the device, resulting in a powerful improvement of the R_{dson} x Q_g figure of merit even from the early stages of development of these new components.

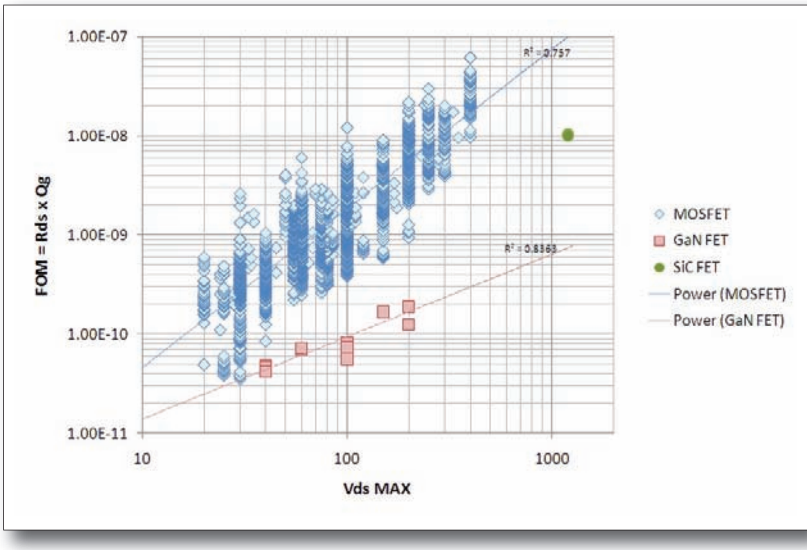


Figure 2: FOM (R_{ds} x Q_{gd}) for various FET devices currently available on the market. The dots represents different devices, the continuous line is a linear extrapolation for different V_{ds}. It is clear that eGaN will be even more competitive for the future generation which will have much higher BV

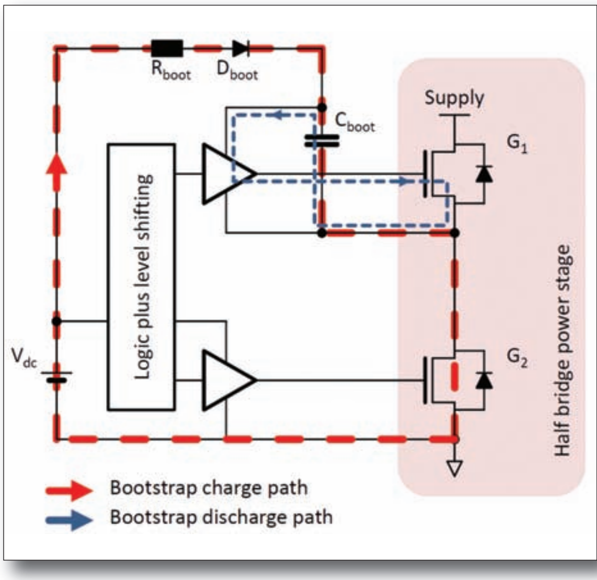


Figure 3: High voltage half bridge and gate driver, shown are high and low-side driver, bootstrap circuit and level shifter

GaN devices manufacturers forecast an improvement of one order of magnitude for this FOM of the 2014 devices with regard to the Silicon performances in 2009, allowing for significant efficiency improvements in high switching frequency converters and driving towards stronger overall miniaturization.

Although GaN is populating many of the recent headlines and has outstanding FOM (see Figure 2), these new technologies will not completely replace current devices, but rather complement them and reach high levels of popularity in specific applications, like high frequency, high power SMPS. Their advantages are not anyway coming for free and sometimes their usage requires knowledge that is new to most. For example all power designers are familiar with MOSFETs gate driver essential features and are aware of integrated ICs like the LM51XX and many others which could be used to effectively drive standard Silicon switches, but not many know the basic characteristics that a GaN FETs driver should have.

GaN driver main characteristics

In principle a gate driver for this new class of devices does not differ much from a conventional MOSFET driver: in both cases this circuit is essentially a power amplifier that is used to interface low output power controllers, which provide a PWM logic signal, to the power switch; additional features include single or double input, with automatic dead-time control.

The gate driver has to accomplish two main tasks: provide suitable voltage levels to drive the switch with low impedance output and high current capabilities and propagate the signal to the low and high-side buffer with correct timing and accuracy. On these two main aspects a dedicated GaN driver should provide some specific characteristics specifically aimed to avoid overstresses and increase switch lifetime: GaN electrical requirements to maintain reliability are highly specific and deeply different from the ones of conventional MOSFETs.

High current capabilities and DC bias

High current sinking/drawing capability of the gate driver is the most important feature of a MOSFET driver, allowing fast charge and discharge of the Miller capacitance in the power switch and ensuring fast transition, thus minimizing the switching losses in the converter. In this case there is no difference in a GaN driver: high peak current and low impedance output are still essential characteristics. Even if the power losses associated with gate charge are largely reduced, Miller cap are still present and

does not scale equally and induce losses that can only be minimised achieving high commutation speed.

Accurate gate driver supply voltage

HEMT eGaN devices allow only small headroom between the recommended gate source voltage and the maximum gate source voltage that they can withstand. For example EPC GaN FETs give the best R_{dson} performances when turned on with 5V V_{gs}, but they allow only 6V maximum gate voltage. This characteristic requires very accurate gate voltage, which is hard to achieve for high-side floating bootstrapped supplies.

From Figure 3 it is possible to observe the basic working principle of a bootstrap circuit; when OUT (source voltage of the high-side FET) is pulled below the controller Vdc, the Cboot is charged following the red bootstrap current path. The final VBS that is released by the boostrap circuit after OUT is pulled up is $V_{BS} = V_{dc}\text{-}Vf_{dboot}+V_{fG1}$. V_{fdboot} is the bootstrap diode forward drop and V_{fG1} is the reverse-direction 'diode' voltage of the GaN device. Due to the intrinsic feature of enhancement mode GaN FETs VfG1 is larger than a Silicon bootstrap diode forward voltage, resulting in boostrap voltage larger than V_{dc}.

To fully exploit the switches R_{dson} at 5V and ensure a reliable operation without exceeding the maximum gate rating, it is necessary to use additional circuitry to regulate the output voltage of the bootstrap circuit. Even for the low-side driver, the stringent requirements on the gate-source voltage pose some issues on the accurate control of the turn on voltage to avoid overshoots and call for some accurate layout design.

Spurious turn on due to high dV/dt

The increased switching frequency of SMPS that employ GaN FET and the much smaller output capacitance Cds introduce some performance advantages, but also some driving constraints. The presence of really fast dV/dt (that can reach peaks of 30 kV/µs) together with the unfavourable ratio between gate drain capacitance and gate source capacitance (the EPC60V has almost comparable Q_{gd} and Q_{gs}) increase the risk of Miller turn-on and direct conduction of the half bridge leg to dangerous levels.

In order to address this issue, the pull down resistor of the driver should be kept as low as possible: down to values below 1Ω. On the other hand, an option to adjust the pull-up resistor is also often required to improve EMI and overshoots control. The typical MOSFET driver has a single output driver and the correct tuning of pull-up and pull-down resistor is obtained through the use of an anti-parallel diode. Due to the stringent constraint in pull-down resistance and voltage levels, the GaN FET driver needs to split gate driver output for turn-on and turn-off paths.

High-side driver constraints

When driving GaN FETs, the dead-time generally hurts the overall efficiency of the converter. The reason is that the GaN devices have no standard anti-parallel diode (only majority carriers are involved in GaN device conduction) so there is zero recovery time and a reverse forward drop higher than the one in reverse diode for the Silicon MOSFET.

The approach taken by the industry to keep the diode conduction at a minimum level, given the really fast turn off time of GaN FET (typically lower than 10 ns) is to not apply the usual dead-time before turning on the other device in the same leg, but to fine tune the driver for a 5 ns ± 2 ns dead-time interval that minimises the body diode conduction losses and guarantees safe operation without shoot-through in the leg.

In order to provide such an accurate dead time, the propagation delay matching between high-side and low-side is a parameter of concern. Generally keeping it in a range of 2 ns or less is enough to prevent the shoot through or cross-conduction in the circuit.

LM5113 makes GaN simpler

Until few months ago the only viable solution to use GaN FET in an accurate and reliable way was to deepen the knowledge of the aforementioned issues and eventually build a discrete components gate driver. Now National Semiconductor introduces the first dedicated gate driver for GaN devices.

National's LM5113 is a 100V bridge driver for enhancement-mode GaN FETs that implements all the necessary techniques to ensure safe and reliable operation. It has a fully integrated high-side bootstrap diode that further simplifies the application development and minimises PCB area occupation. The device also regulates the high-side floating bootstrap capacitor voltage at approximately 5.25V to optimally drive GaN power FETs without exceeding the maximum gate-source voltage rating.

The LM5113 also provides independent logic inputs for the high-side and low-side drivers, enabling flexibility for use in a variety of both isolated and non-isolated power supply topologies. The fast propagation delay and the superior delay matching make it suitable for high speed applications and minimization of reverse diode losses. The device also features independent sink and source outputs for flexibility of the turn-on strength with respect to the turn-off strength. A low impedance pull down path of 0.5Ω provides a fast, reliable turn-off mechanism for the low threshold voltage of GaN power FETs, helping to maximise efficiency in high frequency power supply designs (see Figure 4/5).

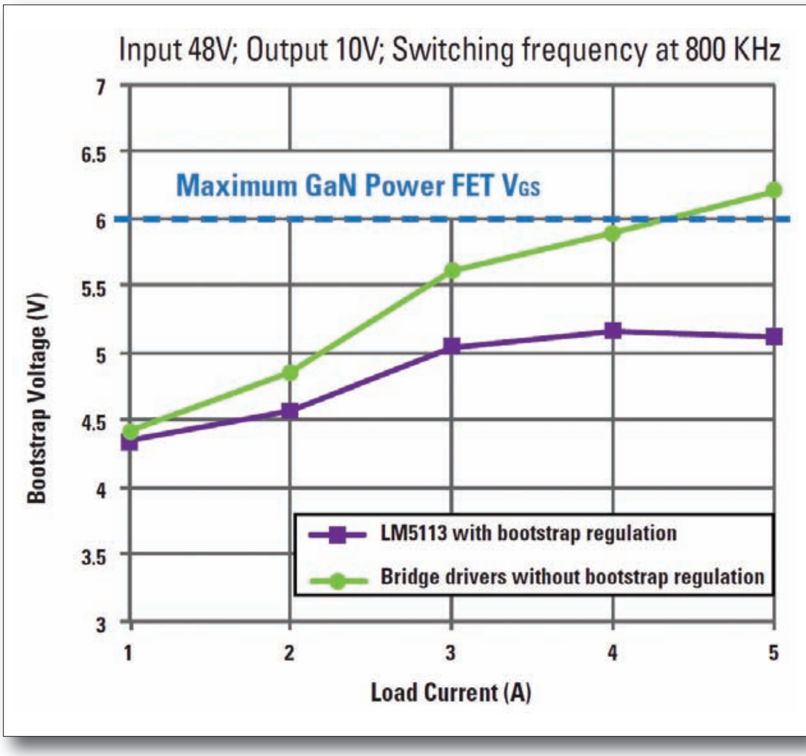


Figure 4: **Output regulation of bootstrap voltage**

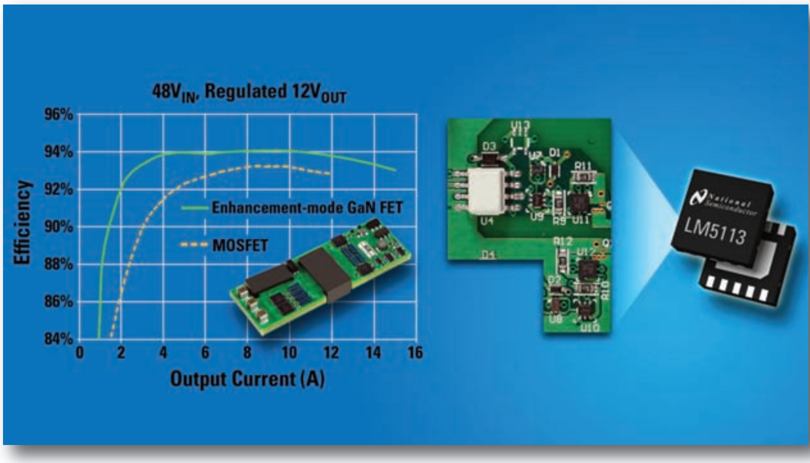


Figure 5: Size comparison of the LM5113 with a discrete solution

Conclusions

A short overview of the technological improvements in solid state switches for power electronics over the years, mainly driven by the endless research for the missing efficiency percentage point, has shown how GaN technology has strong proliferation potential, thanks to a combination of advantages which make it now very appealing in a broad range of application. The most visible effect of this explicit potential is the response of the semiconductor industry, which is now starting to propose dedicated driving solutions.

National's LM5113 was born after this careful analysis of the incredible potential of GaN devices, and recognizing the issues arising in driving these devices in the most appropriate way: leveraging the performance improvements and avoiding the dangerous overstresses. As we have seen, the dedicated driver allows the power application designer to be safe in terms of accurate gate-source voltage control, dead-time management, spurious turn-on control, and driver asymmetry; a number of additional capabilities complete an important basket of crucial features which can be found in this new class of integrated drivers for GaN devices, delivered into the most miniaturized footprint.

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Recent GaN Based Power Device Developments

There is an increasing demand for high density power conversion solutions. At the same time, economic, political and social pressures are mounting to increase the power delivery efficiency. For a given power device technology, these two performance metrics, efficiency and density are in conflict and lead to a performance figure of merit of efficiency * density. As silicon based technology is reaching maturity, a truly revolutionary change in this performance FOM requires that a fundamentally new power device technology platform be introduced. **Michael A. Briere, ACOO Enterprises LLC under contract to International Rectifier, USA**

Since the advent of the spontaneous AlGaN-GaN based high electron mobility sheet formation, first discovered by M. Asif Kahn in 1991 [1], significant efforts have been made to bring the inherent capabilities of this exciting material system to bear in practical semiconductor power devices. The combination of high breakdown field strength due to the wide band gap of the III-nitrides, high electron mobility, as well as an unusually high channel electron density, yield a remarkably compelling drift resistance. Such devices also benefit from the reduced gate charge requirements involved in switching the devices on and off. Probably the most exciting attribute of the system involves the easily isolating nature of the inherently lateral devices, permitting unprecedented monolithic integration of power systems.

The trade off between density and efficiency is largely a question of switching frequency. As the switching frequency increases, losses are compounded in the power converter from three main sources: namely the driving losses, the current*voltage overlap of the power devices and the dissipative capacitive losses of the device output impedance. In addition there are core losses in the magnetic element of the output filter inductance. To achieve improved efficiency, it is therefore imperative that improvements in the power device behavior, particularly the requisite input and output charge levels involved in the device switching between on and off states be achieved (Q_{switch}).

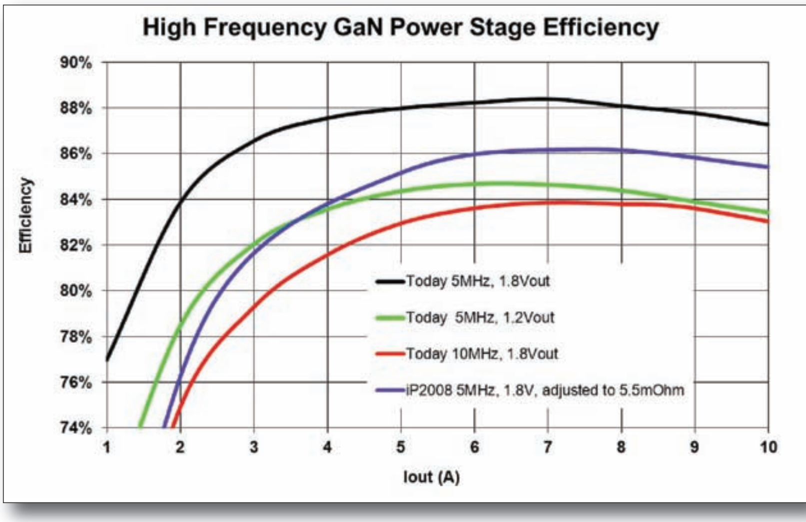

Figure 1: Measured conversion efficiency (including driver and output filter losses) for 12 V_{in} POL DC/DC converters using first generation GaN based 30 V rated switches with a R_{on}*Q_g FOM of 30 mΩnC (including package contributions)

Advantages for DC/DC converters

For low voltage DC/DC converters, the density of the power converter is determined, to a large extent, by the size of the output L-C filter. The higher the switching frequency, the smaller the required inductor needed to maintain a given output ripple voltage and the smaller the output capacitor needed to deliver a given transient load current. This situation is compounded for loads such as many CPUs which have very high transient current requirements in order to support the dynamic voltage supply needed. Of course, lower switching losses can be achieved by reducing the semiconductor power switch die size and therefore the die capacitances. This would, however, limit the current handling capability both from a power efficiency standpoint and thermal limitations, due to the finite device specific on-resistance (R_{dson}) induced ohmic losses. Therefore, just as in the case of the power converter, the power device exhibits an equivalent performance figure of merit: R_{dson}*Q_{switch}.

Early results for point of load (POL) DC/DC converters using first generation GaN based devices from International Rectifier have been discussed previously [2,3]. In fact, commercially available products have since been released utilizing this technology platform [3]. The early results for high frequency single stage POL conversion resulted in 86 % peak efficiency at 5 MHz and 81 % efficiency at 10 MHz for 12 V_{in} to 1.8 V_{out} conversion. At the time, simulations suggested that significant improvements in conversion efficiency could be achieved through improved driver and output inductor performance. Figure 1 shows the results of such improvements in the driver circuitry, using the same GaN based device technology platform. As can been seen, this has resulted in about 2 % increase in efficiency at peak loads and 4 to 6 % improvements at light loads, in good agreement with the earlier simulation based predictions. An excellent performance is therefore achieved using first generation GaN based devices with R_{on} * Q_g FOM of 30 mΩnC.

As discussed elsewhere [4], there is a further need to dramatically increase conversion density, in support of many

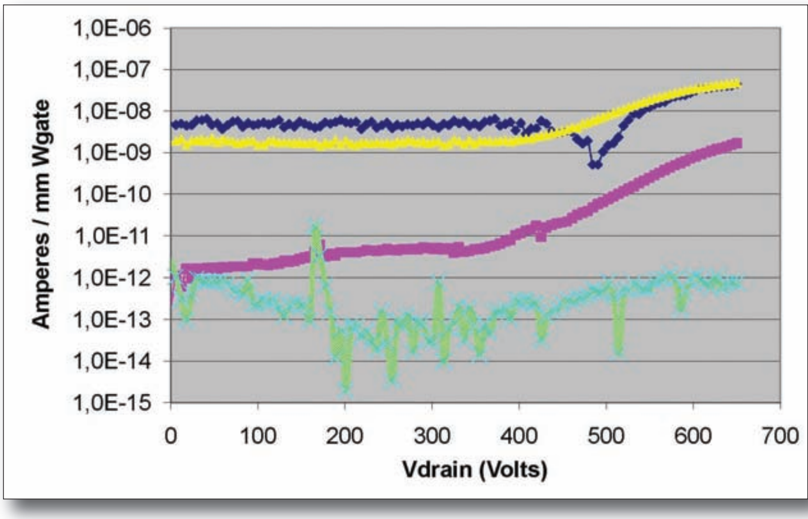

Figure 2: Measured room temperature reverse bias leakage current from drain, source, substrate and gate for a prototype 650 V rated IR GaN device

(>32) core processors. In order to optimize the performance of these complex loads, it is best to provide each core with its own 12 V_{in} power supply. This would require a conversion density of some 75 to 100 A/cm^2 and a subsequent conversion frequency of 30 to 75 MHz. In order to achieve a single stage conversion efficiency of 12 V_{in} to 1.2 V_{out} of 88 %, this frequency requires a power switch FOM of some 2-3 mΩnC. This is an order of magnitude less than the limits possible for Silicon based power devices [5,6], but reasonably above the limit for 30 V GaN HEMT based switches of about 0.5 mΩnC.

It is important that the leakage behavior of the GaN based devices be comparable to that of the incumbent Silicon technology based alternatives. Figure 2 shows the reverse leakage behavior of a prototype 650 V rated GaN based HEMT device at International Rectifier with V_g = -10 V at room temperature. As can be seen, the leakage is well behaved and is dominated by the current from between source and drain, with the leakage levels below 0.1 µA/mm up to the 650 V rating. It is impressive to see that the substrate and especially the gate currents are well suppressed throughout the reverse bias voltage range of the device which had 100 mm gate width and a gate length of 3 µm.

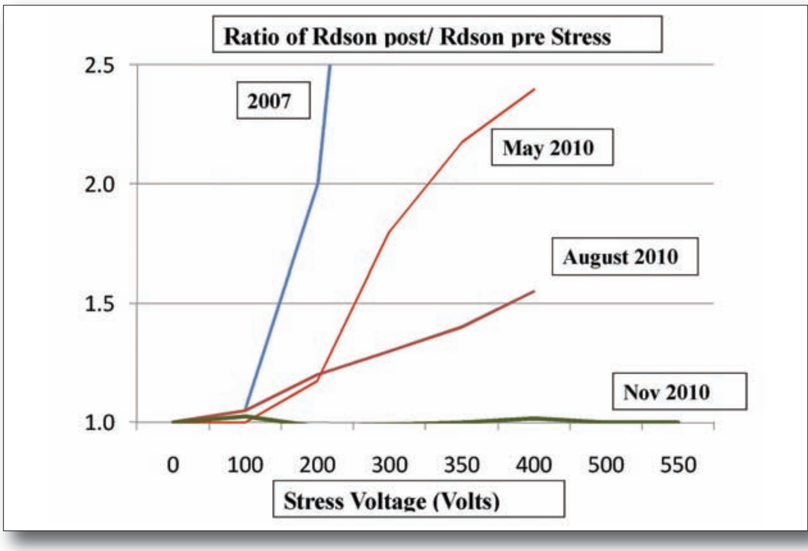

Figure 3: Measured improvement in the dynamic R_{dson} effect, defined as the ratio of R_{dson} post and pre applied reverse bias stress voltage, as measured within 1 µs of the transition between the off-state and the on-state

High device ruggedness

Device ruggedness in application conditions must also remain uncompromised with respect to expectations established by the incumbent Silicon based technology. Large forward biased safe operating area is an important indication of such robustness and has been demonstrated o 600 V prototype devices to 10 A at 600 V for 100 ns, with V_g-V_p of 4 V. Device stability under accelerated stress conditions for extended periods of time is essential for acceptance in the power electronic community. To date, over 10,000,000 device hours of reliability data has been collected on the low voltage devices released to production by IR in early 2010, with up to 10,000 hours per device. No intrinsic premature device failures have been found to date and parametric stability has been excellent. In addition, initial reliability studies of high voltage GaN based devices have also shown excellent parametric stability to 2000 hours.

It is imperative that such catastrophic failure mechanisms such as the "inverse piezo-electric effect", found in metal-semiconductor gated GaN based HEMTs [7] be eliminated. Under all applied accelerated stress conditions, no physical degradation of the AlGaN barrier has been found in IRs insulated gate GaN based devices as is commonly reported for metal-semiconductor gated devices.

Commonly reported trapping related instability phenomenon such as current collapse or dynamic R_{dson} [8] must likewise be minimized beyond concern. Figure 3 shows the R_{dson} measured within 1 µs of applying varying reverse bias conditions for early 600 V GaNpowIR prototypes. As can

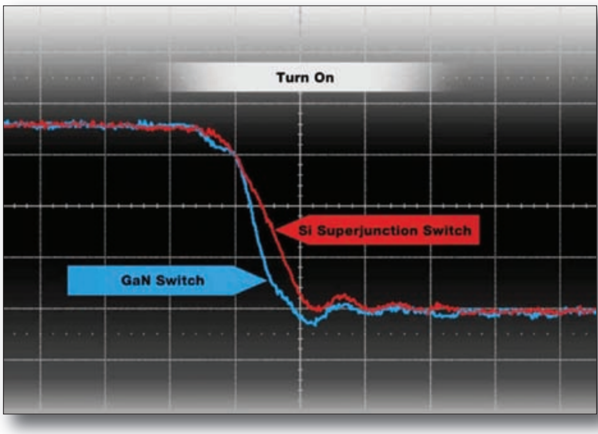

Figure 4: Turn on waveform for a 430 W capable power factor correction circuit boosting from 150 to 350 V at 100 kHz using 120 m_ GaN switches or state of the art 99 mΩ Silicon superjunction MOSFETs. The timescale is 10 ns/div, the voltage scale is 100 V/div and the average current is 1 A (in both cases a SiC diode was used for the rectifying function)

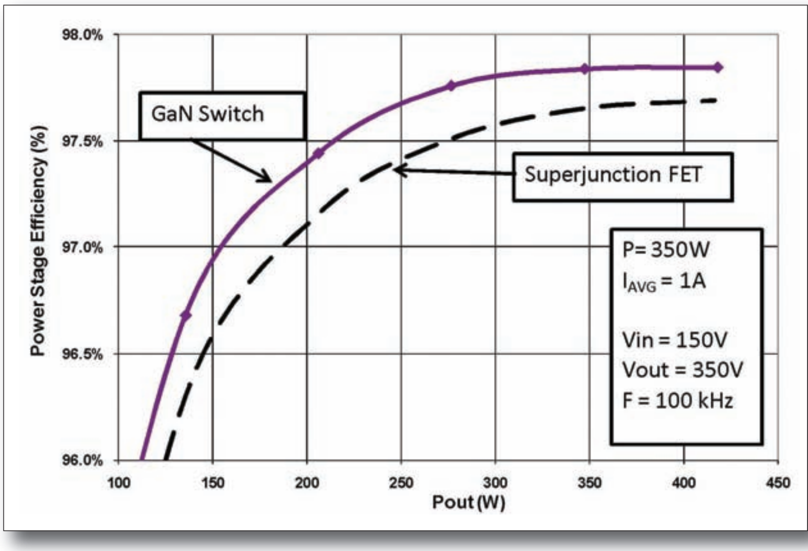

Figure 5 above: **Measured conversion efficiency of the boost circuitry for a 430 W capable power factor correction circuit boosting from 150 to 350 V at 100 kHz using 120 mΩ GaN switches or state of the art 99 mΩ Silicon superjunction MOSFETs (in both cases a SiC diode was used for the rectifying function)**

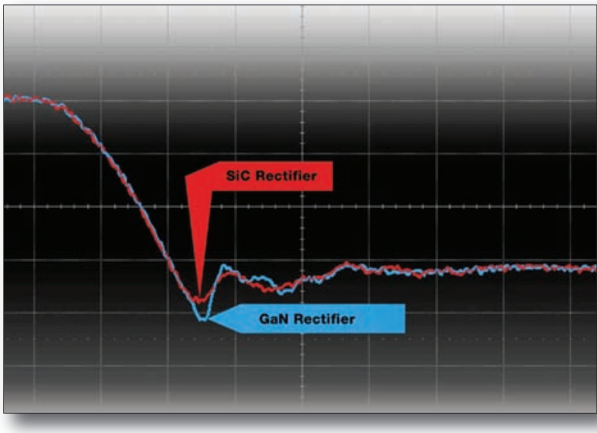

Figure 6: **Switching waveforms of an early prototype 600 V GaN cascaded rectifier and a best in class SiC Schottky diode. Both devices are rated for 6A with a V_f < 2 V at 150°C. The difference in measured Qr (which is predominantly capacitive) is a few nC**

be seen, the commonly reported trapping effects have been effectively minimized in this platform.

GaN and PFC

Lowering the cost of high performance AC/DC power supplies using power factor correction (PFC) boost circuitry is another application where GaN based power devices provides an unprecedented combination of efficiency, switching speed and cost effectiveness. Figure 4 shows the turn on waveform of a 600 V cascaded GaNpowIR switch used in the control switch function of the PFC boost circuit, compared to that of a state of the art 99 mΩ Si superjunction MOSFET, both in TO-220 packages. As can be seen, the GaN based switch has superior switching characteristics. This manifests itself as improved power conversion efficiency, as can be seen in Figure 5, for this 430 W capable PFC circuit operated at 100 kHz. Cascoded GaN based rectifiers provide essentially the same performance as high cost SiC Schottky diodes, as shown in Figure 6, for 6 A rated devices. This will allow wide adoption of high efficiency PFC circuits. In addition, the availability of lower cost, high-performance wide band gap semiconductor based switches and rectifiers will promote wide spread adoption of efficient converters, such as inverters for distributed solar power generation, saving 2-3 % in energy loss [9], representing a full decade of improvement in solar cell efficiency.

HV GaN and drives

One of the greatest opportunities for world-wide energy conservation involves the use of efficient permanent magnet motors driven by inverters in appliances, such as air conditioners, refrigerators and clothes washers. In addition, the increasing electrification of transportation drive systems will require improved inverter electronics for both the primary and auxiliary electronic systems. The incumbent technology for these motor drive applications are Silicon based trench IGBTs. Figure 7 shows a comparison between state of the art 600 V rated Silicon trench IGBTs and prototype first generation 600 V rated GaNpowIR devices in terms of conduction*switching loss FOM. As can be seen the GaN based devices perform remarkably better. What is truly exciting is that an order of magnitude further improvement in performance for GaN based power devices is potential over the coming decade.

One of the key FOM for the power switch if the specific on resistance. Figure 8 shows a possible roadmap for performance improvements for GaN based devices, leading to a factor of 8 improvement compared to state of the art Silicon based superjunction devices in the available on resistance in a given package (e.g. TO-220) over the next four years.

Conclusions

The availability of cost effective, high quality, robust, high performance GaN based power devices will enable truly innovative improvements in power electronic density, efficiencies and costs in the coming years.

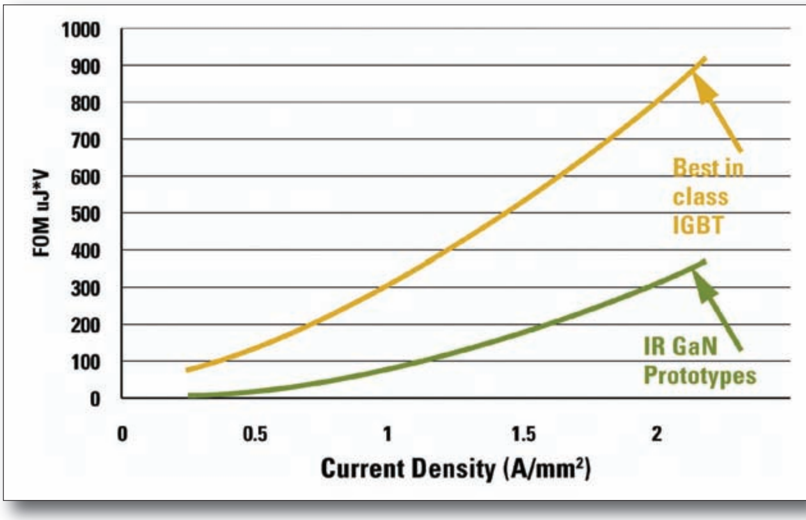

Figure 7: **Measured performance comparison between state of the art 600 V rated silicon based trench IGBTs and prototype first generation 600 V rated GaN based devices in terms of conduction * switching loss figure of merit [V_{on}*(E_{off}+E_{on})] vs current density at 25°C**

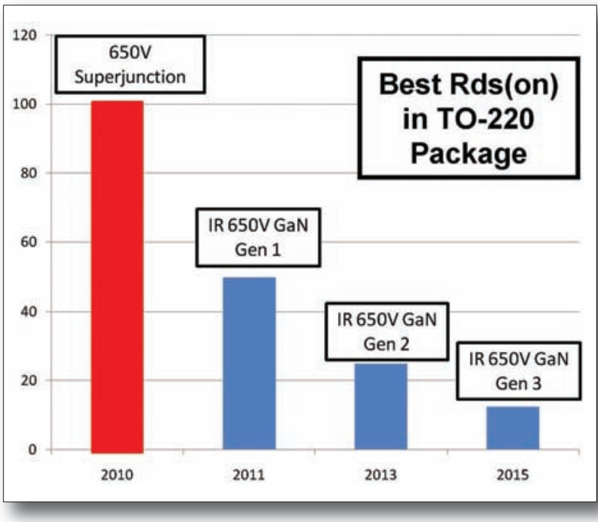

Figure 8: Possible 650 V GaN based power switch performance roadmap, showing an 8 fold improvement over state of the art Silicon devices within the next four years

From more efficient solar panel based inverters to higher density efficient permanent magnet based motion control systems to lighter weight and denser inverters for electrified vehicles, as well as next generation integrated DC/DC power supplies for electronics, GaN based power devices will revolutionize the industry. This technology platform strongly supports the objective to enable lower system costs to promote the adoption of efficient systems that significantly reduce worldwide power consumption [10].

It is tempting to relate the introduction of these devices to that of power MOSFETs some 30 years ago, which revolutionized power electronics by enabling compact cost effective switching regulator based power supplies. However, it appears more likely that this paradigm shift will have aspects of the greater character of the revolution in data processing which occurred through the development of large scale and very large scale integrated circuits. This is due to the intrinsically integrated nature of the lateral GaN based device platform, allowing integration without performance compromise, a feat not possible in vertical silicon based power device technology. This will provide an entirely new level of performance, density, robustness and cost effectiveness. This paper was one of the highlights at PEE's Special PCIM 2011 Session "High Frequency Switching Devices and Applications".

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Choosing Inductors for DC/DC Regulators

When selecting an inductor for the output storage element of a switching DC/DC regulator, a designer can be faced with a bewildering array of options from different suppliers and even within the ranges of one supplier. Using a 'point of load' converter as an example, this article explains what the choices are and what advantage one choice might have over another. The principles generally read across to all inductor applications. **Paul Lee, Director of Engineering, Murata Power Solutions, Milton Keynes, UK**

A common requirement is to convert one DC level to another lower level at high efficiency without isolation. At high power, a modular, 'point of load' buck switching converter from one of the many suppliers is economic but for low power, many designers opt for a circuit utilising a control IC and the necessary discrete components. Excepting 'charge pump' circuits, an inductor is invariably required to store energy to maintain the output during the 'dead' periods of the usual pulse width modulation regulation methodology. Figure 1 shows the basic configuration.

Looking in the Specs

The IC application note will often guide selection of an appropriate inductor with a recommended part number from a magnetics manufacturer. However, this part may not be optimum for the actual application and may not be in the required mechanical format. If just an inductance is given, the designer must look even further into the specifications of available parts to select something appropriate. Also, inductance is a starting point that may need to be adjusted, perhaps to fall in line with preferred values or for the designer to understand how the circuit responds if the inductance is at the extreme of its tolerance.

Normally the inductance value is chosen to achieve a particular inductor ripple current according to:

$$\Delta I = U\, t / L$$

where ΔI is the peak to peak ripple current, U is the output voltage less free-wheeling diode or synchronous rectifier drop, t is the maximum 'off' time of the main switch and L is the inductance. Note this is load-independent.

Transients and EMI

A large inductance value will therefore give a low ripple current which is absorbed by the output capacitor giving a low output ripple voltage generated across the capacitor ESR and ESL. When electrolytic capacitors with relatively high ESR and limited ripple current ratings were the norm, it was important to keep the ripple current low and hence inductance high. However, monolithic ceramic or film capacitors are now common with extremely low ESR that allows much higher ripple currents for minimal heating and output ripple voltage. Smaller inductance values are therefore feasible giving correspondingly lower DC resistance and higher current ratings. A smaller inductance also allows faster load transient response time.

There are three problems associated with allowing a very high ripple current. Firstly, because the ripple is superimposed on the DC load current through the inductor, it can cause additional ohmic losses in the wire and AC losses in the core. Secondly, the peak of the ripple must not exceed the saturation limit for the inductor, and finally at a light load the 'valley' of the ripple current will cross over zero. For synchronous rectifiers that can conduct in both directions, this current can go negative and stay 'continuous'. For diode rectifiers, the current stops or goes 'discontinuous' for a part of each switching cycle for loads less than this minimum value. The transfer function of the converter changes as this minimum load value is crossed and the loop compensation has to be designed to give stability in both conditions. This normally results in a compromise if only in increased circuit complexity.

Having decided on an inductance, the inductor current rating must be chosen. Values in data sheets will be for a continuous current for either a given temperature rise or for a given inductance drop as the inductor starts to saturate. As mentioned, there may be significant ripple current so this must be allowed for. If temperature rise is the limit, it may be possible to run at high ripple currents or in excess of the rated load current if airflow is available. Note that different manufacturers rate their inductors for different

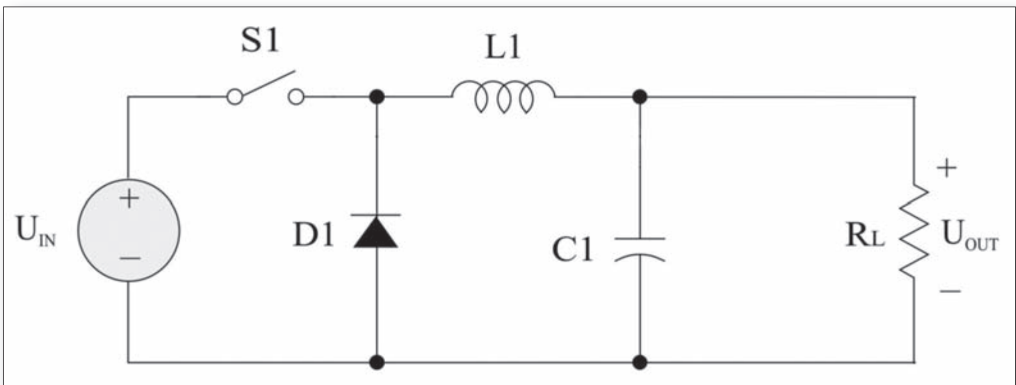


Figure 1: Buck converter schematic

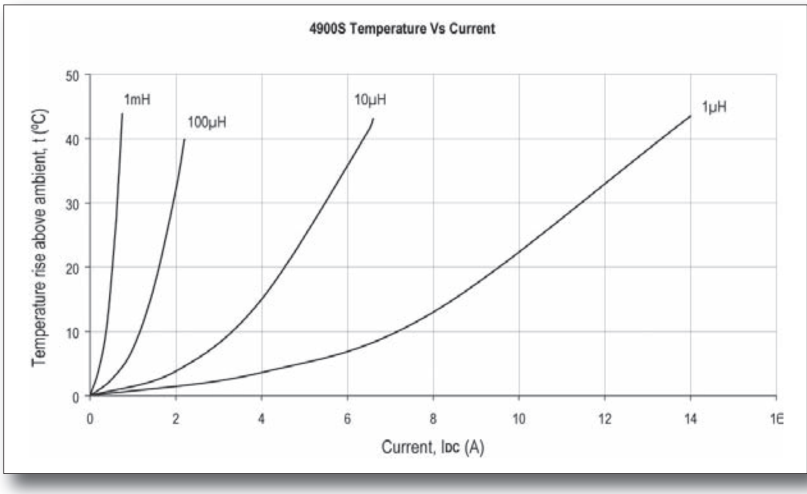


Figure 2: Current vs temperature graph for an example inductor

temperature rises and percentage drop in inductance. For example, Murata Power Solutions use 40°C rise and 25 % drop respectively. From their data sheets you can see that the 4900S series is saturation-limited as their 11.8 A rated part has a rise of only 33°C at this current (see Figure 2).

It is worth examining also how inductance falls off with current. Different core materials and shapes saturate more or less sharply. Transient and overload conditions should be considered which might, with some materials, cause a sudden, considerable drop in inductance with resultant damagingly high peak currents in semiconductors. Powder cores generally saturate more gradually though they will have higher core losses with AC applied. It should be appreciated that saturation levels vary strongly with temperature typically dropping 20 % between 25°C and 100°C. A correctly specified inductor will factor this into the rated current value.

Some powder materials have a designed-in 'swing' of permeability so that at very light load, the inductance is much higher and therefore can give lower ripple current which helps with the mode change stability problem mentioned previously.

Inductor DC resistance will be quoted in data sheets which will cause volt drop and dissipation. The value will normally be quoted at 25°C and will rise with the temperature coefficient of copper at about 0.4 % / K. Again, a correctly specified inductor will include this effect in current rating.

A little-considered specification is the impulse voltage rating of an inductor. In low voltage applications, this is not an issue. However, some buck converters drop rectified mains voltage to logic levels and the inductor can see up to around 400 V end-to-end at high frequency. The construction of the inductor should be such that the wire breakdown voltage is appropriate, particularly between winding start and finish where the wires may cross. MnZn ferrite is essentially conductive having a resistivity of typically 1-10 Ωm and may provide a 'sneak' path for breakdown. NiZn ferrite has high resistivity, typically 105 Ωm and is used for the bobbin-less drum core styles of inductor but for a high voltage application a style with an insulating bobbin would still be recommended. If not stated in the data sheet, the inductor manufacturer should be able provide an impulse rating from product qualification testing.

Another characteristic to consider is the self-resonant frequency (SRF) of the inductor that can be in the 100s of kHz for high inductance values. Any simulation of the circuit should include parallel winding capacitance and DC resistance for best accuracy. Data sheets will give inductance and SRF so the capacitance can be derived from

$$C = \frac{1}{4\pi^2 \,(SRF)^2\, L}.$$

Any inductor is a potential source of radiation. Where this may be an issue, a toroidal core would be preferable with a distributed gap such as Murata Power Solutions' 3200 series. A ferrite drum core such as utilised in their 2800 series is usually lowest cost but its open construction can lead to EMC problems. The necessary core gap is effectively the distance between the bobbin flanges outside of the winding. Some suppliers provide inductors with optional ferrite sleeves that provide screening such as the Murata Power Solutions 2300 series shown in Figure 3. If the electrically 'hot' end of the inductor is arranged to be the 'start' of the winding, that is, the innermost layer, the outer layers provide a degree of natural electrostatic screening. Look for the dot or marking on the body of the inductor to signify which terminal is the start. A degree of magnetic screening can be achieved with a copper 'belly band' around the component but it would normally be more cost effective to select a part designed to contain magnetic fields.

Stubborn EMC problems could also be addressed by the placement and orientation of the inductor. Unscreened tracks under the component should be avoided. Remember that copper ground planes only provide electrostatic screening,

Figure 3: Use of ferrite sleeves example, Murata Power Solutions 2300 series

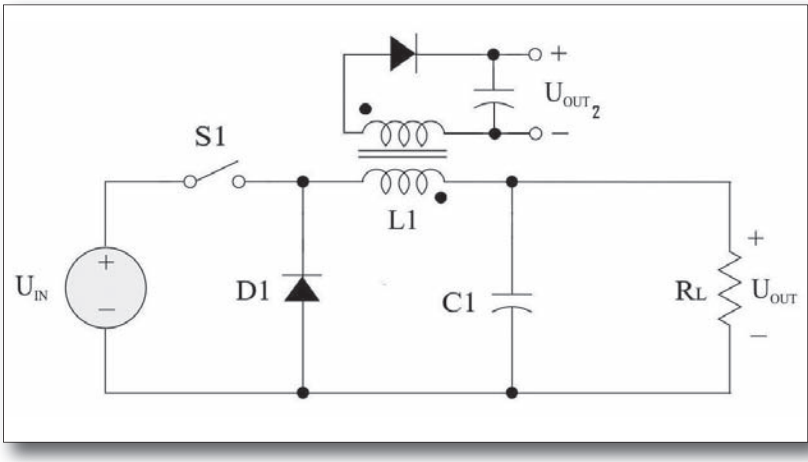


Figure 4: **Generating an auxiliary low power voltage**

that is, they provide a diversion route for capacitatively coupled currents. Attenuation of electromagnetic coupling requires a ferrite screen or a copper band that effectively provides a 'shorted turn' to the external field.

Observe peak voltage

An interesting fact is that the peak voltage across the inductor when the main switch S1 is off is essentially constant with load and line variations in a buck converter so if you add an extra winding to the inductor and peak rectify the waveform as in Figure 4, you get a low power, isolated and semi-regulated voltage for free!

Finally there is a choice of mounting style. Through hole and SMT parts are available with a variety of terminations allowing for high vibration environments and low profile versions such as the Murata Power Solutions 2700T series (Figure 5) are available at just 1 mm high for the most space sensitive applications.

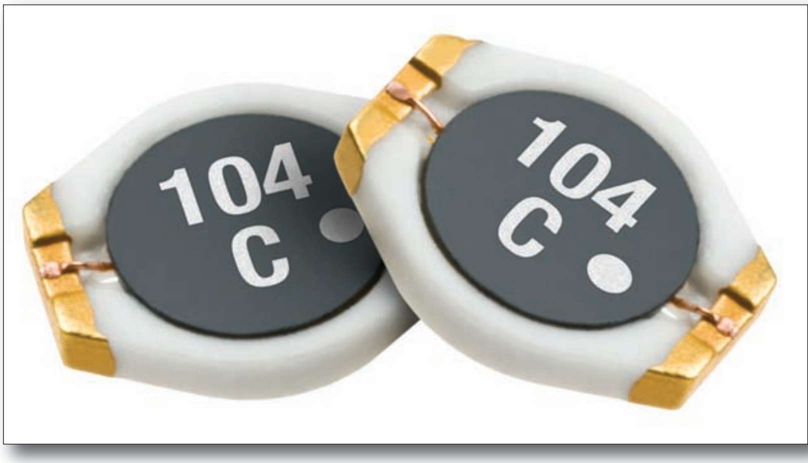
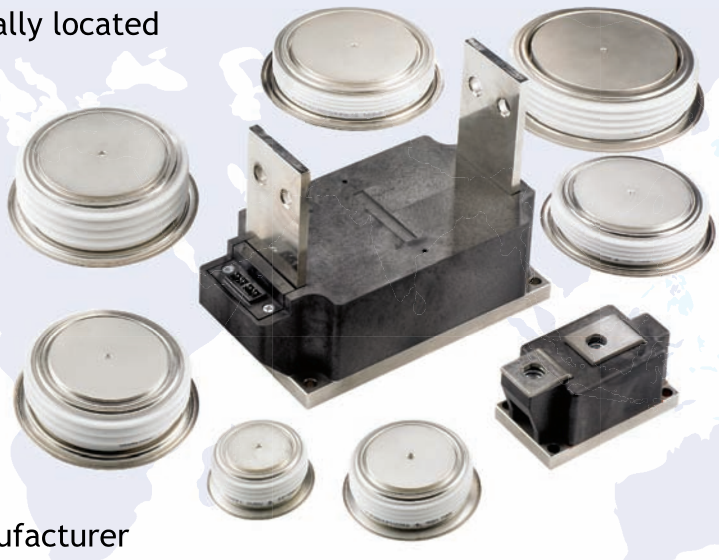


Figure 5. **Space constrained applications benefit from low profile surface mount inductors**



Reliable and Cost Effective Solution without Baseplate

Power modules are used for a wide range of different applications. For some applications the power density, the efficiency or the price is one of the key factors. But for all of them reliability is the major factor. This article describes the difference between modules with and without a baseplate and how reliability and thermal conductivity is affected. **Patrick Baginski, Field Application Engineer, Vincotech, Unterhaching, Germany**

Massive baseplates were used for power modules in the past. These can be made of Copper or Aluminum Silicon Carbide (AlSiC). Nowadays where costs play an important role, also modules without an additional baseplate can be found. Figure 1 shows a *flow* 0 module without and a *flow* 2 module with baseplate. Here, for the left picture, just the direct bonded copper (DBC) is mounted with a thermal interface material to a heatsink.

State of the art

DBC substrates have been proven for many years in power electronic applications. The advantages of DBC substrates are high thermal performance, Silicon matched coefficient of thermal expansion (CTE), high current capability, high voltage isolation and low capacitance between front and backside.

Aluminum Oxide (Al_2O_3) DBCs are often soldered to an additional baseplate when using more than one DBC. For some bigger modules with a rectifier, brake and an inverter part the first two mentioned parts are soldered to one substrate and the inverter IGBTs and freewheeling diodes to another substrate.

AlSiC baseplates are often used for tractions applications where plates made out of copper usually find place into power modules for all other applications. The differences of both materials that belong to modules are the physics. Especially the CTE and the thermal resistance are of interest.

Thermal conductivity

Thermal conductivity is the property of a material describing its ability to conduct heat. It is measured in watts per meter-kelvin [W/mK]. A high thermal conductivity is necessary to keep the average temperature of the die low. Also the temperature ripple is influenced by the conductivity of the material. Figure 2 shows a cross section of DBC and baseplate modules without housing and also without soft gel.

These materials have different thermal resistances. Therefore the temperature drop from the die to the case is not linear. Conductivities are between approximate 20 W/mK and 400 W/mK as shown in Table 1.

Clearly, DBC modules with an AlN ceramic conduct heat much more effectively, so the heat transfer from the top to the bottom is far better. What's more, a comparison of modules shows that the copper baseplate's thermal resistance is lower than that of AlSiC baseplates. It follows that a material with higher thermal conductivity helps decrease the die's junction temperature.

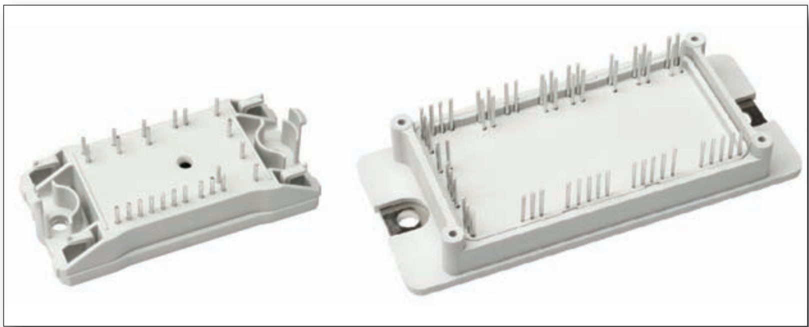


Figure 1: DBC based *flow* 0 power module (left) and *flow* 2 with copper baseplate

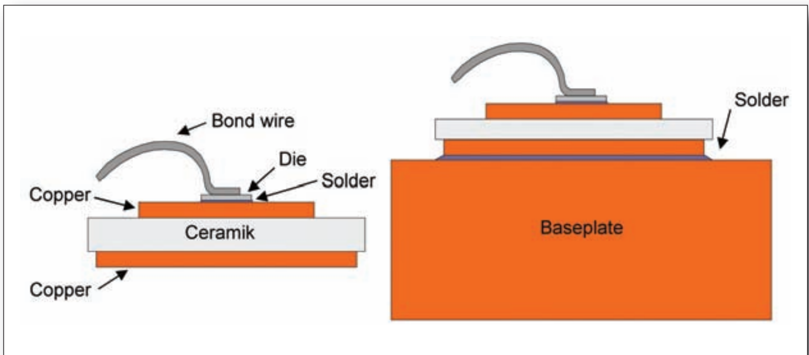


Figure 2: Cross section of DBC and baseplate module

Coefficient of thermal expansion

The section above described the thermal conductivities of materials commonly used in power modules. The CTE is also critical to a power module's reliability. Thermal expansion is the tendency of a material's volume to change in response to temperature change. The CTE for all materials described below is measured in [10^{-6}/K]. Copper, for example, has a higher CTE than Silicon. Given the same temperature increase for both materials, copper expands about six times more than silicon. Table 2 shows key materials used in power modules.

Values of soft gel, housing and also bond wires are not discussed here. It should be mentioned only that also the CTE of the bond wires makes a contribution to the life time of modules.

The CTE of Al_2O_3 for example is closer to the Silicon compared to copper. Although the CTE of AlN is closer to that of Si, which reduces stresses in die attach materials,

Part	DBC module		Baseplate modules	
Die [W/mK]	Silicon [148]		Silicon [148]	
Solder [W/mK]	SnAg [62]		SnAg [62]	
DBC [W/mK]	Al_2O_3 [25]	AlN [155]	AlN [155]	
Solder [W/mK]			SnAg [62]	
Baseplate [W/mK]			Cu [401]	AlSiC [180]

Table 1: Thermal resistance of module materials at 25°C

Part	DBC module		Baseplate modules	
Die [10^{-6}/K]	Silicon [2.8]		Silicon [2.8]	
Solder [10^{-6}/K]	SnAg [22.1]		SnAg [22.1]	
DBC [10^{-6}/K]	Al_2O_3 [8.2]	AlN [4.5]	AlN [4.5]	
Solder [10^{-6}/K]			SnAg [22.1]	
Baseplate [10^{-6}/K]			Cu [16.5]	AlSiC [8.4]

Table 2: CTE of module materials at 25°C

the stresses are actually higher in the joint between the copper baseplate and DBC. This is due to the increased CTE difference between the net CTE of the AlN DBC and Cu baseplate, which leads to a larger bending of the power module.

Typical substrate and baseplate material's CTE may be several times that of Silicon and other semiconductors. This difference causes thermal stresses in the devices, solder interconnections, and substrates because the mismatches are frozen during the assembly process of the module at high temperatures, especially during the soldering process.

These stresses can cause mechanical and fatigue failure, or changes in operating behavior. Mismatched CTE is not the only source of thermal stress in the device. The shear strength and stiffness of the joint material and the joint area are also factors. In IGBT power modules, the joint between the DBC and baseplate is much larger than the joint between the semiconductor and DBC, so it is more prone to failure brought on by thermal cycling. Consequently, the DBC may delaminate from the baseplate, which can cause thermal resistance to increase, temperature to rise, and crack propagation.

Finally, a module's compromised ability to remove heat may culminate in thermal runaway. Residual thermal stresses in the DBC-baseplate stack can also cause a bimetallic effect that bows the module. The deformation is concave because the copper baseplate's CTE is greater than that of the DBC. This creates a gap between the module and the heatsink, which increases this interface's thermal resistance even after thermal grease is applied. The bimetallic effect is proportional to temperature. The grease may be squeezed out if a thermal compound is applied and the module is mounted to a heatsink. This is known as the pump-out effect. Pre-bent, convex baseplates such as those used in *flow* 2 modules can compensate for this packaging-induced phenomenon.

Wear-out failures

Different wear-out failures are observable. But only the failures due to CTE or in other words mismatches of the stack are taken into account. This means that this failure can occur between every material with different temperature expansion coefficients.

Delamination starts from the edges of the solder joint and works to the middle of it (Figure 3). This is because of the absolute movement of the materials. Small chips and small solder joints do not have that high delamination compared to big solder joints. A good solution could be to assemble two small semiconductors instead of one big. This needs a bit more space but reduces the wear-out failure as well as the thermal resistance. The same method can be considered when it is necessary to solder DBCs to baseplates. Also here smaller DBCs helps to decrease the delamination of solder layers. Both failures cause an increase of junction temperature and reduce the lifetime of the module.

Power modules' reliability also depends on the load profile. An uninterruptible power supply (UPS) furnishes a constant load so the average junction temperature remains very stable. Also, a UPS works at 50 or 60 Hz so the die's ripple temperature remains low. All materials only see one cycle when the application powers up. After a few minutes, the entire application will run at a constant temperature. This is the best-case scenario for all components. In other applications such as welding, the power is switched on and off repeatedly. The devices generate losses that heat up the system, which cools down again while the power is switched off. This exposes components to many temperature cycles, which causes solder layers to delaminate.

There are several ways to counteract this effect. Smaller chips may be paralleled as described above, or the module may be oversized so that it generates less loss and therefore less heat. An efficient way of solving the problem is to use a module whose materials' CTE are well matched.

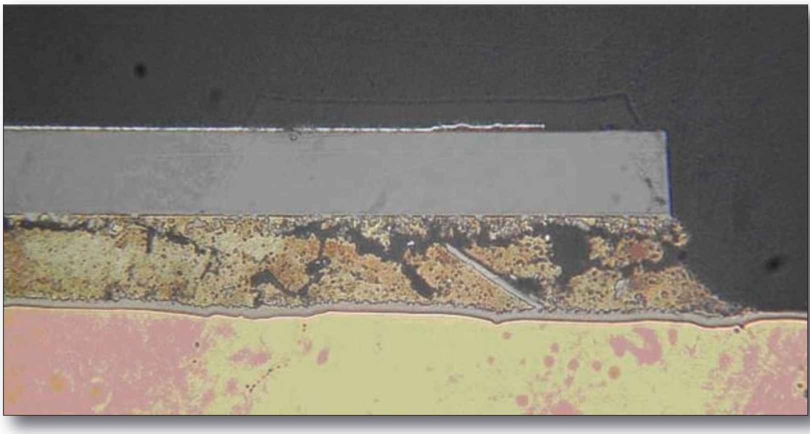


Figure 3: Delamination of solder layer

Reliability of different concepts

Again, reliability is a function of CTE values and the number of temperature cycles. To gain a better understanding of this we need to look closer at thermal spreading as shown in Figure 4.

The red lines represent thermal spreading. It is obvious that the thermal spreading in each case depends on the next layer below.

Vincotech subjects each module to battery of quality and reliability tests during the qualification process. Two different tests assess the various materials' thermal expansion properties.

One is the load or power cycling test. It

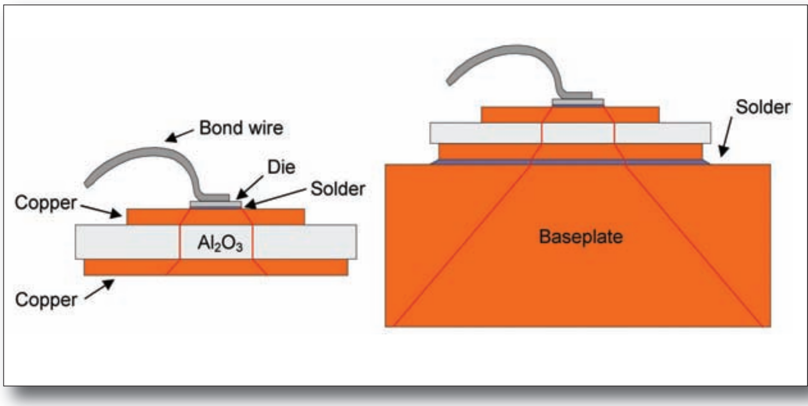


Figure 4: Thermal spreading of DBC (left) and baseplate module

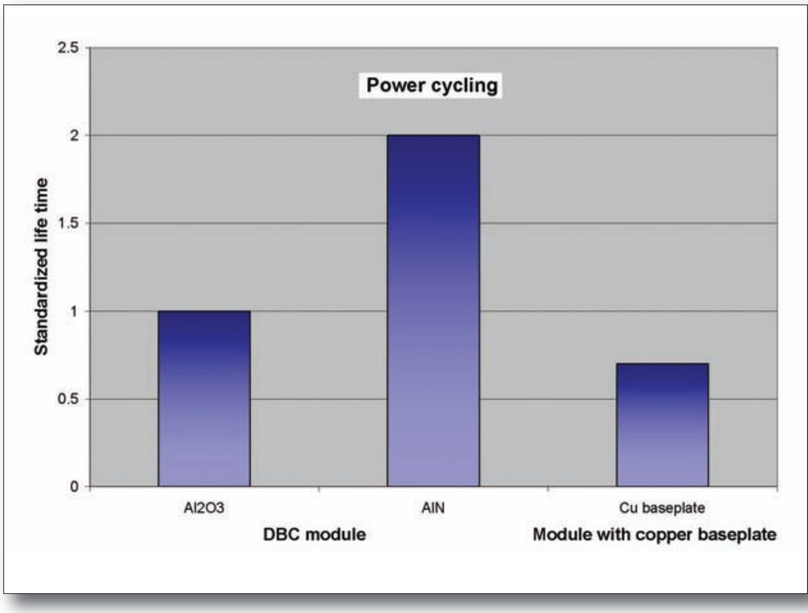


Figure 5: Reliability data standardized to a DBC module with Al2O3 DBC

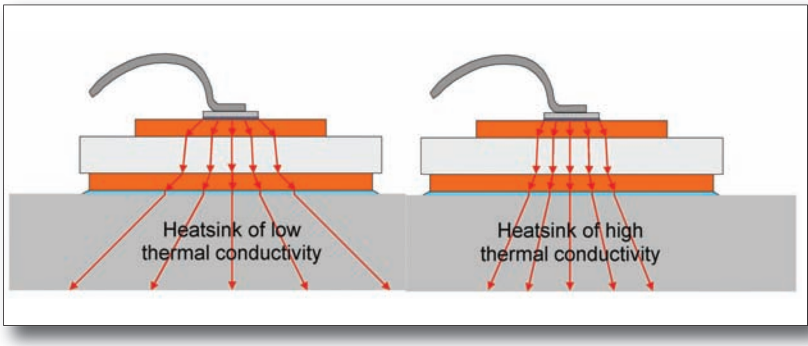


Figure 6: Thermal spreading with low (left) and high conductivity heatsink (water cooled)

places considerable stress on the connection between the bond wire and semiconductor, generating substantial losses and a temperature drop from the semiconductor to the module's case. The other test is the thermal shock test where the module is moved from a cold to a hot chamber for a certain time within a transition time of less than 30 seconds.

Figure 5 shows reliability data standardized to a DBC module with Al_2O_3 DBC. Test conditions for all three modules were equal. Also the chip size and number of chips were the same. The temperature difference of each cycle was 100K, starting from 25°C to 125°C. The failure criteria was an increase of $R_{th(j-c)}$ of 20% due to delamination.

This description of the CTE phenomenon and how it relates to reliability would not be complete without mentioning heat-driven expansion. The solder joint must absorb the Silicon, DBC, and baseplate's expansions without failing. The challenge is to design a solder joint thin enough to ensure a low drop in temperature, yet thick enough to absorb the movement of joint materials. The temperature drop from top to bottom also has to be taken into account. The highest temperature is at the top where the die resides and lowest at the bottom where the heatsink sits.

Influence of thermal spreading

Again, each downward layer influences thermal spreading. The R_{th} values stated in Vincotech's datasheets are measured with a water-cooled heatsink. It absorbs energy very well, so very little thermal spreading occurs. Figure 6 illustrates thermal spreading in a water-cooled and in a conventional heatsink.

The specifications for all modules are given for a water-cooled heatsink. This means the Rth values in the datasheets are worst-case values. If an air-cooled heatsink is used instead, thermal spreading is higher, which results in a better $R_{th(j-h)}$ value. The heatsink is not the only component to influence thermal spreading; the given thermal compound is also a contributing factor.

Conclusion

Having examined different variants of modules, we can draw the following conclusions: The longest component life may be achieved by keeping temperature ripple low. The load and environmental conditions are key factors. The fewer the number and the lesser the extent of thermal expansions, the greater the reliability. The CTE of materials should match. If thermal capacity is not an issue, a module without a copper baseplate is the right choice.

Modules with baseplates may be necessary if brief spikes of high energy are expected. Each downward layer of material layer influences thermal spreading. R_{th} values stated in the datasheet are measured with a water-cooled heatsink and indicate the worst-case scenarios.

Counting Methods for Lifetime Calculation of Power Modules

Various counting methods are applied to extract amplitude and number of thermal cycles from a mission profile. Unfortunately the estimated lifetime may change, depending on the used method. To suggest the correct counting technique for lifetime calculation the finite element method (FEM) was used to simulate the thermo-mechanical stresses, experienced by the power module when it is submitted to a given thermal load.
Krzysztof Mainka, Markus Thoben, Oliver Schilling, Infineon Technologies AG, Warstein, Germany

The lifetime prediction of power IGBT modules based on realistic mission profiles is an important issue for power electronic systems that are used in applications with high lifetime requirements. Among the most demanding are railway or hybrid electrical vehicles. Figure 1 shows a schematic with all steps that are necessary during this process [5].

The mission profile transfers into motor speed, varying phase currents and DC-link voltages in the inverter. In combination with the electrical properties of the power module a power loss profile can be calculated. In combination with the thermal behaviour of the power module and the cooling system these losses are generating temperature profiles of IGBTs and diodes. The details of the lifetime estimation approach have been described in [3,5] and are not repeated here.

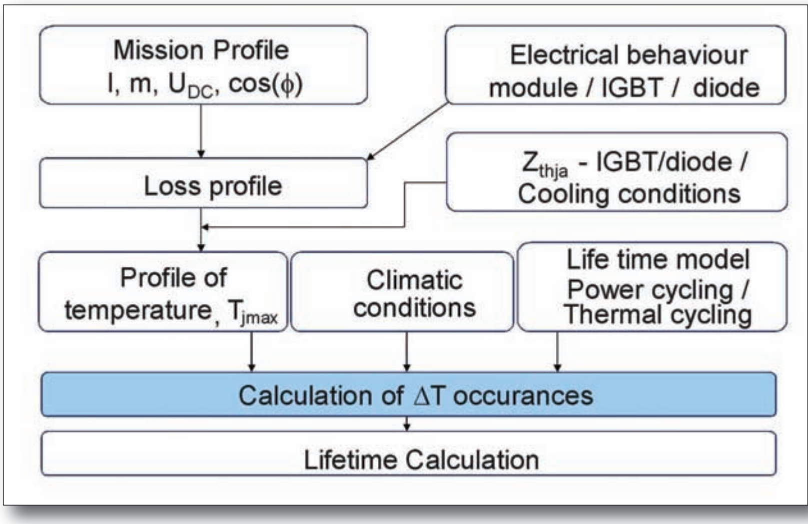


Figure 1: General approach for lifetime estimation

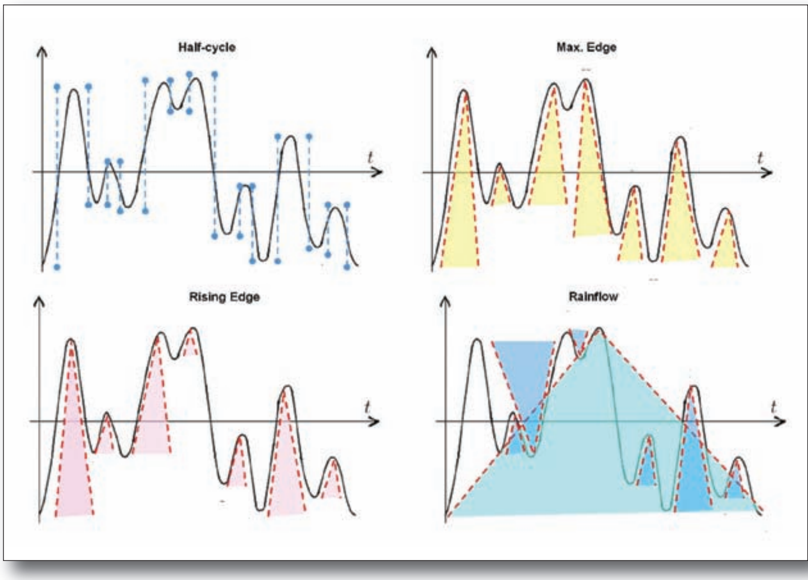


Figure 2. A graphical interpretation of different counting algorithms for an example of temperature waveform

Since the impact of ΔT has the dominant influence on reliability, it should be extracted correctly from the temperature profile. An important challenge of the process is the selection of cycle counting algorithm, because the estimated lifetime may vary, depending on the used method [4].

Various counting methods

There are lots of different counting methods like level crossing counting, peak counting, simple range counting and rainflow counting. The commonly used methods in the lifetime estimation, considered here, are:

- half-cycle peak through counting
- maximum edge peak through counting
- rising edge peak through counting
- rainflow algorithm.

The typical temperature profile is not a single, isolated temperature cycle, but a combination of many superimposed events. Entangled multiple cycles cause that their separation is not necessarily clear. However, different cycle counting algorithms interpret the cycles differently as depicted in Figure 2.

All peak-through counting methods analyze consecutive cycles, which correlates directly with the turn-on and turn-off the IGBT. In the half-cycle method, the different slopes are counted as a half cycle. In the maximum edge method, tone pair of rising and falling edge, is regarded as one cycle defined by maximum swing. For the rising edge method, every subsequent rising edge is counted as a cycle, while falling edge are ignored. The rainflow counting algorithm is

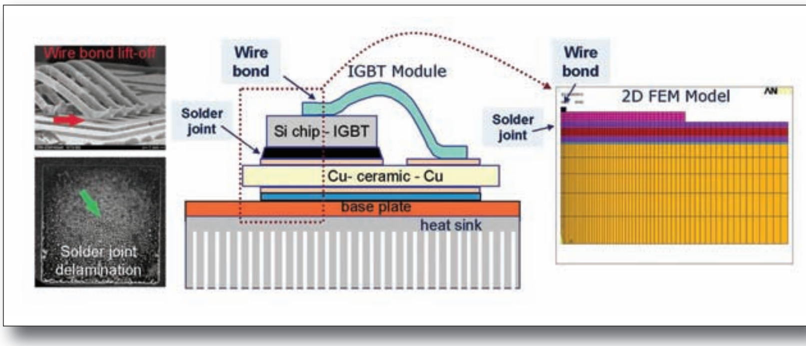


Figure 3: Major failure mechanisms (left), internal structure of the IGBT power module (middle) and FEM simulation model (right)

different from the peak through counting methods. It was developed earlier for the analysis of fatigue data in order to reduce a spectrum of varying stress into a set of simple stress reversals. In the context of lifetime estimation, the rainflow algorithm itself is interesting as a method to reduce a spectrum of varying temperatures to a set of simple temperature reversals. Practical definition of the rainflow cycle counting is explained in ASTM E-1049-85 (Reapproved 2005) [1,7].

FEM simulation of power cycling

The purpose of the FEM analysis is done to find the damage degree under cyclic thermal load like power cycling. The major failure mechanisms in the power module, due the power cycling, that have been taken into account are the fatigue of chip solder joint and the bond wire lift-off as depicted in Figure 3 (left). System solder delamination was not considered here.

Isolated power modules internally consist of a stack of different parts such as power semiconductor chips, substrates with metallization (DCB), base plate, bonding materials - solders and power interconnections - wire bonds and terminals. Based on the internal structure of the power module as sketched in Figure 3 (middle), a two dimensional, axis-symetric FEM ANSYS model was constructed, representing the vertical cross section of the device as shown in Figure 3 (right). In the simulation, nonlinear material properties were considered, especially the viscoplastic properties of solder joints and plastic, temperature dependent material properties for the aluminium wire bond.

The power cycling simulation was performed in two steps:

1. electro-thermal simulation to estimate the transient temperature distribution
2. thermo-mechanical simulation to calculate the amount of damage in the solder contact and bond wires under cyclic thermal load.

Depending on the load's magnitude, solder contact or bond wire undergo certain plastic deformation. Calculated plastic strain or deformation energy converted per temperature cycle sets an increment of damage. Crack propagation inside wire bonds and solder joints occurs in the region where the accumulated inelastic strain energy density per cycle _wp has its maximum. Therefore, the strain energy density, sometimes referred also as plastic work, was used as a measure and calculated from the area of the stress-strain hysteresis loop where plastic and creep damage occurs according to equation 1:

$$w_p = \oint_C \vec{\sigma}\, d\vec{\varepsilon}_p$$

In this formula, σ represents the stress and ε_p the plastic strain.

Counting methods investigation

In order to carry out a comparative analysis of the counting methods, appropriate thermal developments as in Figure 4 were considered.

The methodology of the correct counting technique determination is carried out in a sequence of steps:

- choice of suitable test cycles,
- FEM simulation of selected test cycles to get the Δwp value for wire bond and chip solder,
- application of the investigated counting algorithms to determine the particular temperature swings ΔT_i
- FEM simulation of these temperature swings ΔT_i to get the Δw_{pi}
- summation of the Δw_{pi} values to calculate the equivalent cycle number $\Delta w_{peqv} = (\Sigma_i \Delta w_{pi})$
- comparison of individual results and calculation of the relative error $\delta_{\%}$ between Δw_p and Δw_{peqv} according to equation 2:

$$\delta_{\%} = \left| \frac{\Delta w_p - \Delta w_{pavg.}}{\Delta w_p} \right| \cdot 100$$

Figures 5/6 show the relative error $\delta_{\%}$ by using various counting method for selected test waveforms with different combinations of amplitudes.

A significant dispersion of the results obtained from the different methods is obvious. Quantitative assess can be done based on the results summarized in Table

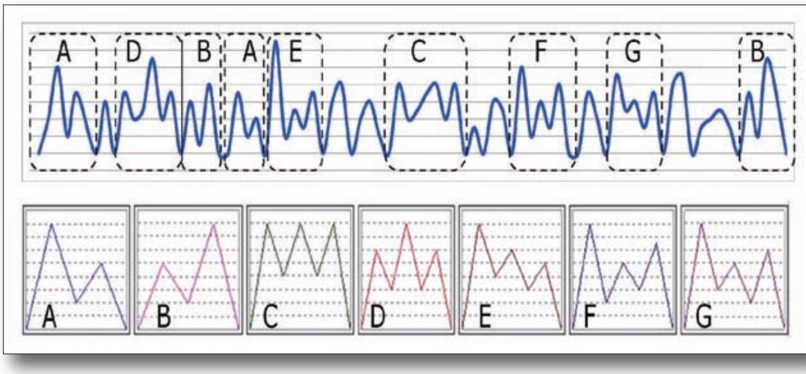


Figure 4: Example of mission profile (upper) and selected test waveforms (lower graph)

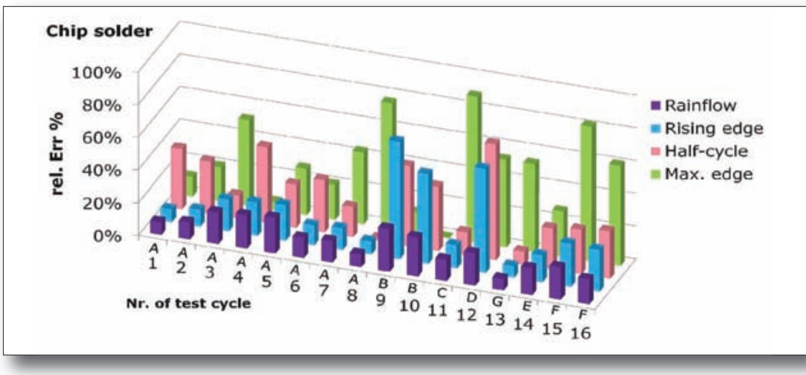


Figure 5: Relative errors ($\delta_{\%}$) in various counting methods for selected test waveforms with different combinations of amplitudes for chip solder

1, which contains the averaged values of relative errors for each counting method.

In addition, the different counting methods are compared based on a special case of a realistic short mission profile, given in Figure 7.

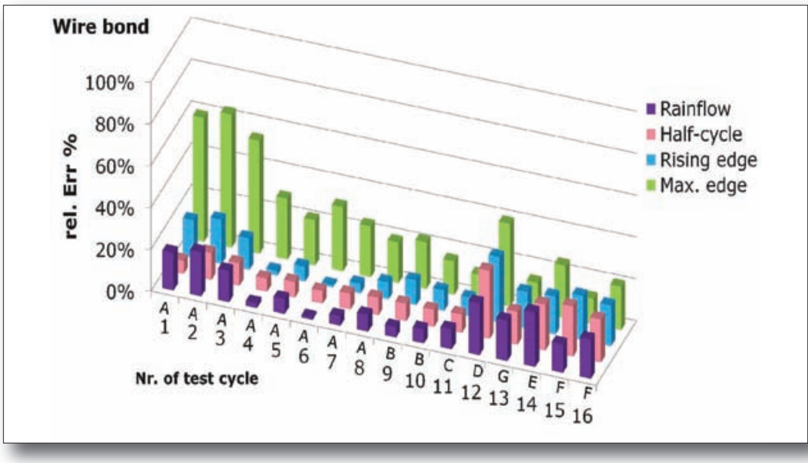


Figure 6: Relative errors (δ%) in various counting methods for selected test waveforms with different combinations of amplitudes for wire bonds

$\delta_{\%avg}$	Rising edge	Half-cycle	Max. edge	Rainflow
Chip solder	25%	29%	44%	15%
Bond wire	15%	15%	28%	15%

Table 1: Compilation of simulation results - averaged relative error $\delta_{\%avg}$

The lifetime wear out in this case is calculated to be far less than the calculation of single selected waveform reveals. This is due to the superimposition of several individual cycles. The profile additionally contains a number of individual cycles. These individual cycles are interpreted identically, independent of the algorithm used.

Table 2 contains the relative error of the calculation results for the short mission profile examined. This error turns out to be smaller than in the previous case of single selected waveform calculation.

The rainflow method shows the smallest error in most cases. On the basis of these results it can be concluded that the rainflow algorithm is advantageous over the peak through counting methods.

Conclusions

Simulation results show that every algorithm of temperature cycles brings some error. Based on the obtained results rainflow method can be suggested as the optimal one, since it gives the best results in terms of reduced error in most cases. The advantage of that method is that it captures not only small cycles, but the bigger one, which is often hidden in the

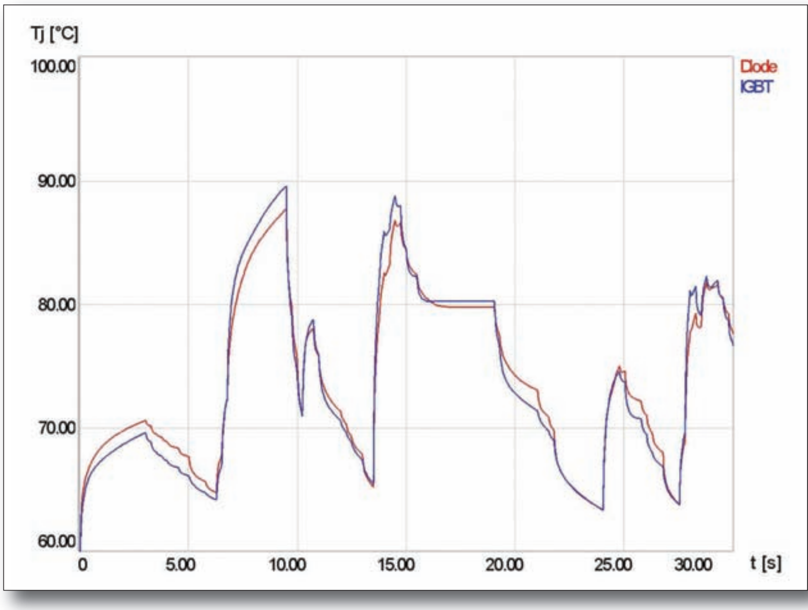


Figure 7: **Example of a short mission profile**

actual runs. In case of adverse ripple-shaped load cases, other investigated peak through counting algorithms miss the largest ΔT, which usually has the biggest influence on the lifetime. For these algorithms manual correction of automatically extracted cycles is required.

	Rising edge	Half-cycle	Max. edge	Rainflow
$\delta_{\%}$	19%	21%	27%	11%

Table 2: **Simulation results for example of mission profile (Figure 7) - relative error $\delta_{\%}$**

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[7] Rainflow Counting Algorithm for MATLAB. http://www.mathworks.com/matlabcentral/fileexchange/3026-rainflow-counting-algorithm

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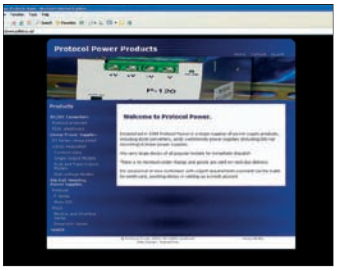

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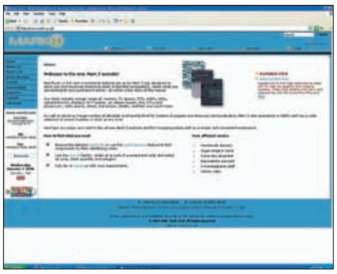

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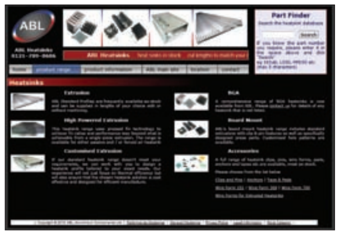

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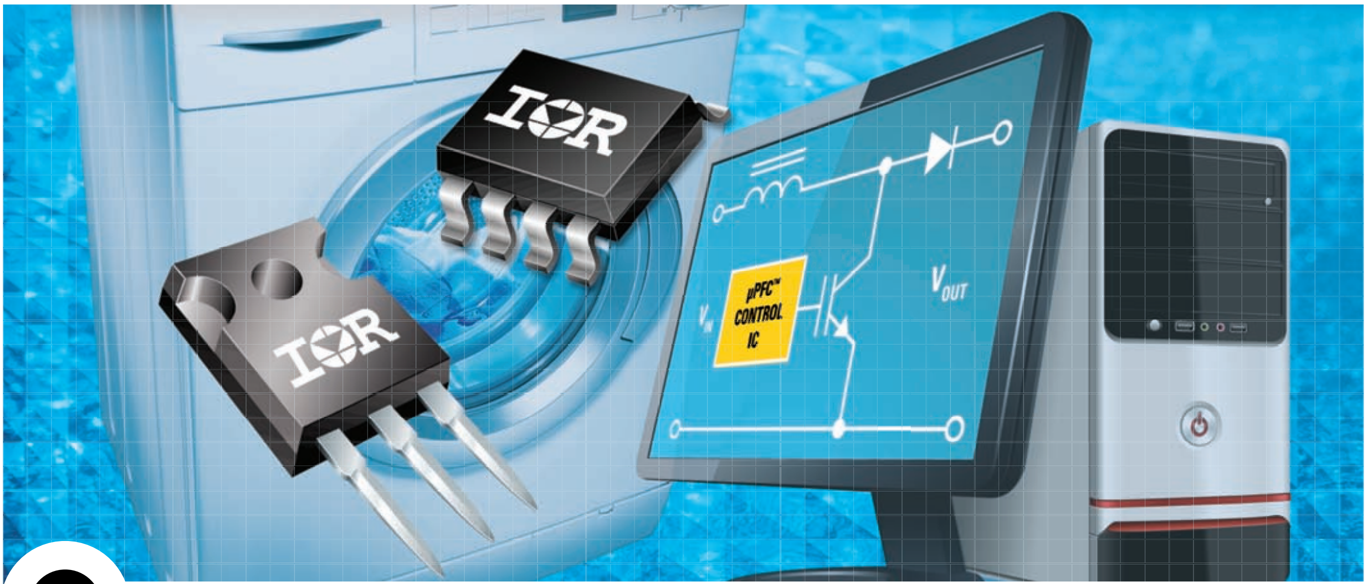

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