# Five "Must-Have Ingredients" For Power Management In Hybrid Electric Vehicles

By Henning Hauenstein, International Rectifier, El Segundo, Calif.

The high-voltage and high-power requirements of electric and hybrid electric vehicles (HEVs) are driving the introduction of new automotive electrical systems. These systems require special electronic devices, semiconductor solutions and advanced packaging options that are very different from those found in the state-of-the-art 12-V electrical systems in combustion-engine cars. This article discusses the challenges faced by semiconductor suppliers in addressing the needs of these new electrical systems. It also provides examples of advanced power management devices and chipsets that International Rectifier has developed to support car and system designers.

## Higher Power Demands Higher Voltage

It is relatively easy for standard combustion-engine-powered cars to satisfy the electrical needs of their onboard systems from a 12-V battery supply and a corresponding 12-V/14-V alternator, which today feeds even the most power-hungry vehicles with enough electrical energy. However, a hybrid electric vehicle (HEV) contains several systems that need far higher power levels.

Whether you're talking about mild, full, or plug-in hybrids, or electric vehicles, the largest power consumer is the electric motor drive that propels the vehicle for a certain period of time without the support of the combustion engine. Therefore, horsepower-intensive electric motors need to be driven by a power supply that is capable of delivering power levels ranging from tens of kilowatts to more than 100 kW over an extended period of time.

It is well known from basic electrical principles that the resistive losses in cables and wires increase with the current in proportion to $I^2$. This consideration becomes important when determining the voltage bus used in a hybrid electric vehicle. Even a state-of-the-art 12-V power bus (power net), like that found in a combustion-engine-powered car, will result in excessively high currents when used in combination with the high-power motors and power supplies required in HEVs. Such high currents would result in a large amount of valuable energy being lost in the resistive interconnections of the 12-V power bus.

To avoid these losses, it's necessary to go to much higher voltages. Hybrid electric vehicles typically use high-voltage power supplies that range from a few hundred volts all the way up to >800 V for electrically propelling larger vehicles such as a heavy SUV. Although going to these high voltages reduces the required current levels, they are still quite high—somewhere in the range of several hundred amperes.

The presence of this high-voltage power bus lead to the introduction of two new power-intensive applications in modern hybrid electric vehicles. One is a dc-ac inverter that converts a dc current into an ac current to drive an electric motor. The other is a dc-dc converter that allows the energy exchange between the high-voltage power net and the 12-V power net.

This 12-V bus is still required even in hybrid vehicles since basically all of the standard automotive electronic systems and applications (like board computers, infotainment, power steering, body electronics, lighting,…) are designed for use with 12-V power supplies. It is impossible and would be too expensive to switch all electronics on board to a high-voltage power concept. Then too, there are the safety issues. It would be unacceptable to employ high-voltage electrical systems powering devices that are within reach and in use by the driver or passenger, as this could suddenly expose them to a several-hundred-volt power supply and high-current source.

## Power Converters Require Optimized Silicon And Packaging

Because they need to manage several kilowatts of power, the inverter and dc-dc converter must employ very sophisticated and efficient power management systems designed with optimized semiconductor devices and advanced packaging. Let's consider some of the specific requirements driving the development of silicon content for these high-power electronic functions.

- **High efficiency in the applications.** We don't want to sacrifice the valuable on-board energy through power losses and heat, since this would defeat the purpose of an energy-efficient vehicle concept.

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- **High current-carrying capabilities.** This can extend up to 300 A or more for power semiconductor devices, which must also be capable of handling high voltages, typically in the range of 600 V to 1200 V.
- **Increased mechanical and electrical performance.** The automotive applications require the electronics to withstand the harsh environment of a car, while safety and protection requirements demand fail proof and safe high-power system designs.
- **Low EMI and low parasitic inductance.** Switching high currents and high voltages will cause very high electromagnetic fields and introduce conducted or transmitted noise/EMI, overvoltage spikes and other disturbances to sensitive electronics such as microprocessors, sensors, safety-critical monitoring devices, etc., which typically operate at low voltages.

Fig. 1 shows an overview of the five key elements that will support the design of high-power inverter and converter systems for hybrid electric vehicles and address the problems listed above.

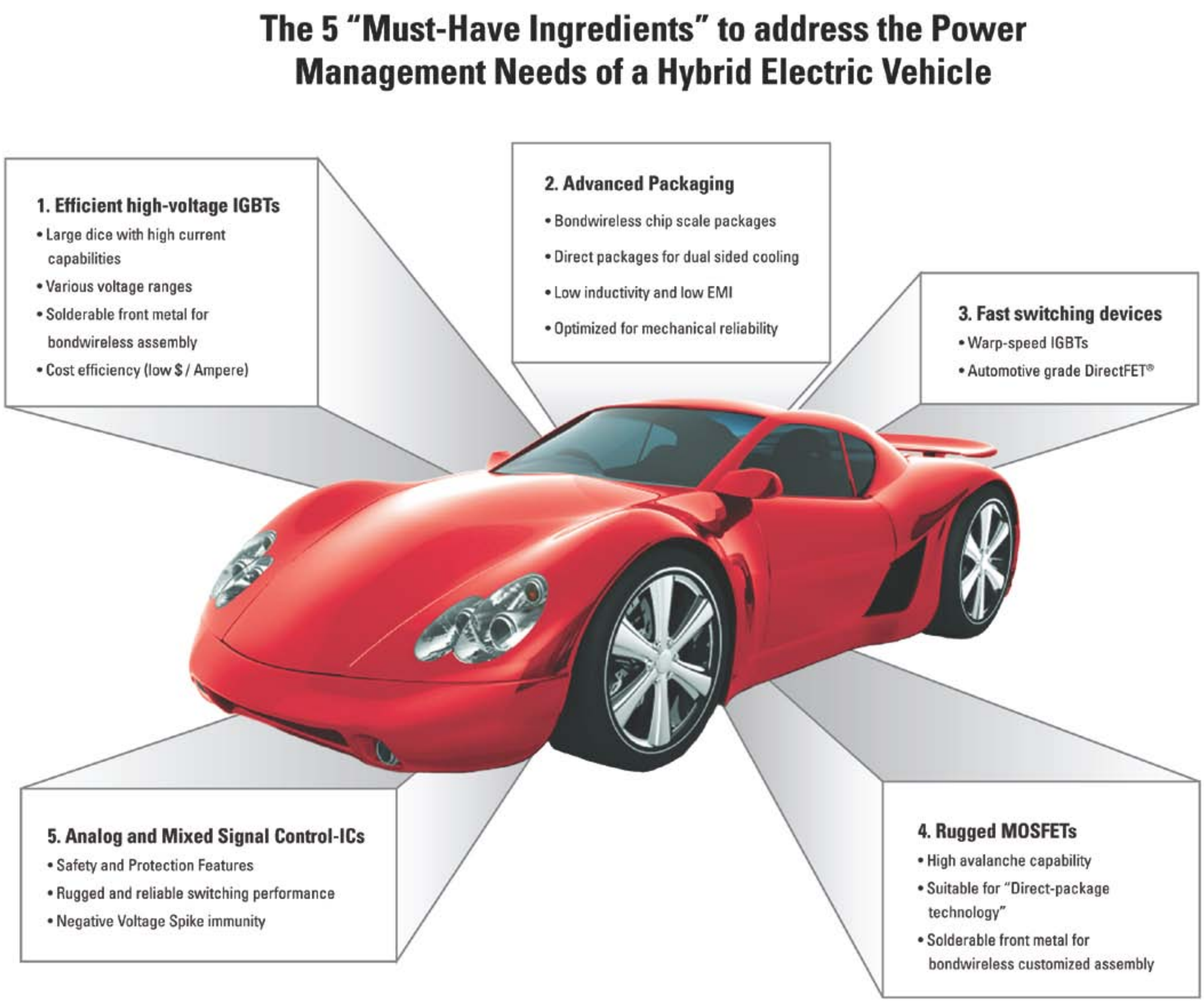


*Fig. 1. There are five absolute requirements for the power semiconductors used to build high-power inverters and dc-dc converters for hybrid electric vehicles. The bulleted items listed under each of these requirements point to the techniques and characteristics that International Rectifier is employing to satisfy these requirements.*

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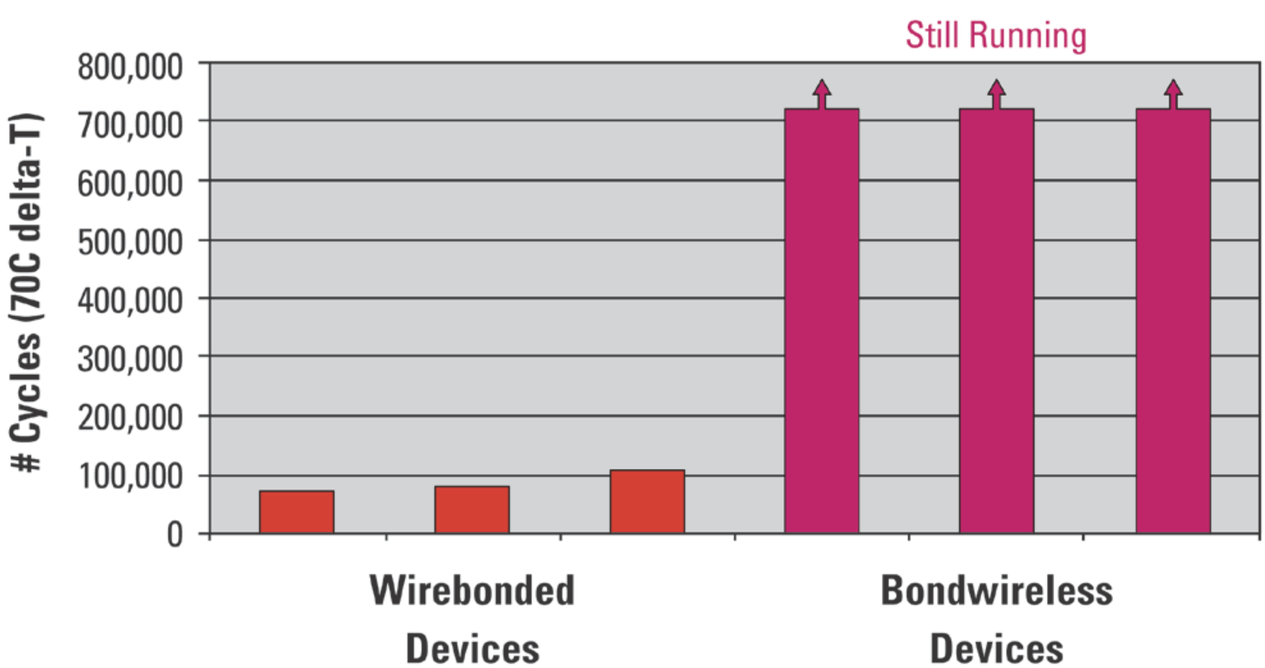
**1. Efficient high-voltage IGBTs**. This type of power switch is needed to efficiently switch high currents of several hundred amperes at voltages in the range of 600 V to 1200 V. Though there are high-voltage MOSFETs on the market they become more and more inefficient at higher voltages due to the increasing channel resistivity of the 2D electron gas under the gate electrode. Therefore, a bipolar device like an IGBT is much more efficient at those current and voltage levels.

But to achieve the required low on-state resistance and to cope with the high currents, very large IGBT devices are needed. Modern state-of-the-art trench devices can provide very low on-resistance at very high-current densities but wirebonds typically used in these devices limit the performance dramatically. Therefore International Rectifier uses a proprietary solderable front metal process to enable our IGBTs to be soldered on both sides, which eliminates the needs for wirebonds in inverter or converter modules.

This solderable-front-metal solution also addresses two more of the requirements listed earlier in this article—reliability and ruggedness. The bondwire-less assemblies provide much higher reliability and ruggedness than traditional wirebonded components because the typical failure mode of "bondwire lift-off" is eliminated. Only solder wear out occurs on a much larger time and stress scale as the remaining failure mechanism. This enables module manufacturers to use smaller devices that can run hotter and withstand larger temperature changes than state-of-the-art wirebonded solutions. The results of such an advanced bondwire-less assembly are shown in Fig. 2.

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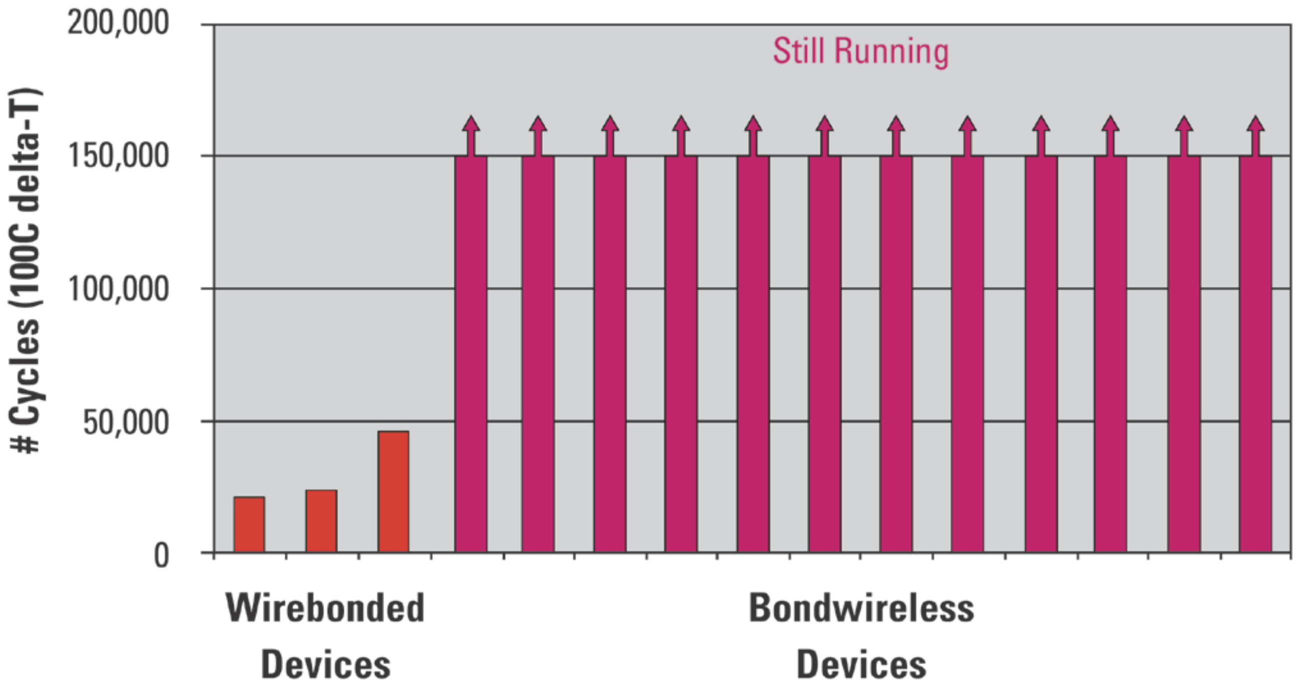


*(b)*

*Fig. 2. Comparison of power-cycling capabilities of wirebonded IGBTs versus wirebond-less both side-soldered IGBTs in a proprietary ceramic-based customer package. The upper and lower graphs show different temperature-stress profiles. Each bar shows an individual device under test.*

On top of achieving greater ruggedness for the IGBTs, use of solderable-front-metal devices also significantly reduces the parasitic inductance associated with wirebonds. As a consequence, the corresponding ringing, which is produced by switching high currents and which introduces noise and EMI, is minimized or disappears completely. Bondwire-less devices from International Rectifier have shown and proven to perform much better under switching conditions than standard wirebonded or plastic-packaged devices. Fig. 3 shows a comparison of IR's DirectFET package versus a wirebonded plastic-packaged device.

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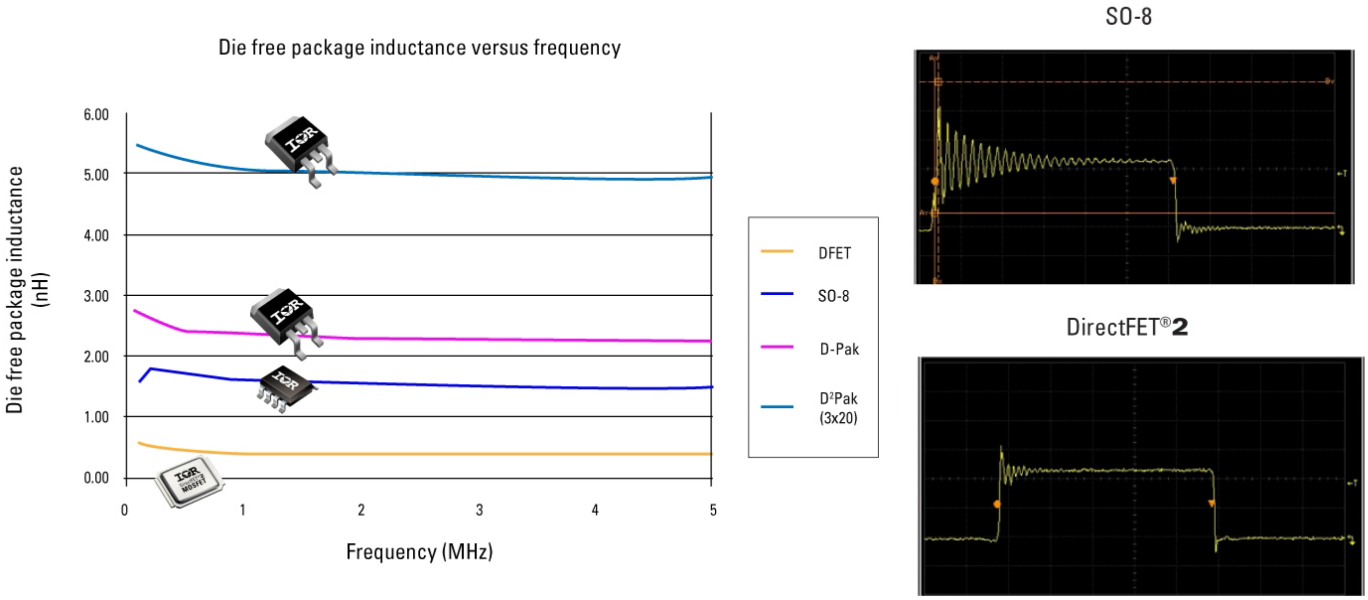


*Fig. 3. Reduced parasitic inductance and ringing demonstrated in IR's proprietary bondwire-less DirectFET package shows improved EMI performance.*

Today's IGBT technology is advancing quickly toward the physical limits of the switch performance of the silicon-process technologies. The usual approach to making IGBTs more efficient—adding more mask layers to ever-more sophisticated devices—is getting more and more expensive. Unfortunately this trend toward higher cost goes in the wrong direction since HEVs already suffer today from the high premium and expensive cost adders of the high-power systems. Therefore, it is important that semiconductor suppliers not only focus on developing leading-edge performance but also keep the cost of the power switches well under control.

The economy of scale that may be achieved by increasing production volumes is often mentioned as the "savior" that will overcome cost obstacles. But that means that in the early stage of product development, high cost will slow down the market acceptance of energy-efficient cars. Therefore, a key focus of International Rectifier's silicon development is achieving a solution that strikes the appropriate balance between performance and cost. Performance needs to be "good enough" to meet the application requirements while the quality, ruggedness and reliability are high and the cost is very reasonable with respect to the "cost per ampere" that a switch can handle.

**2. Advanced packaging.** This is another important ingredient in providing efficient power management solutions. The previously mentioned solderable-front-metal technology is an example of such advanced packaging. The capability to place a rugged and robust solderable-front-metallization on silicon switches (MOSFETs and IGBTs) enables the use of bondwire-less chipscale power packages for all of IR's power switches. The so-called Direct-packages provide superior switching performance, basically zero parasitic inductance, increased mechanical reliability and ruggedness due to elimination of the wirebonds. In addition, this packaging enables cooling of the silicon device from both sides, which is impossible if wirebonds are used on one side.

These packages address the key problems mentioned earlier in this article and offer our customers new design possibilities for their control units and power modules. As illustrated in Figs. 2 and 3, the mechanical and electrical performance is outstanding compared to wirebonded state-of-the-art solutions. In addition, the small size and weight of our Direct-packaged silicon offers additional cost-reduction potential on a system level.

**3. Fast switching devices.** These are also a very important requirement for hybrid electric vehicle applications. While motor-drive inverters typically switch at a moderate 6 kHz to 10 kHz, the dc-dc-converter and battery-charging devices tend to use much higher frequencies in the range of 100 kHz to 200 kHz. These switching frequencies enable increases in the efficiency of the buck/boost converters, while reducing the size of the passive components (inductors/capacitors) in those systems. Unfortunately state-of-the-art IGBTs are best suited for high-current and high-voltage switching at frequencies well below 100 kHz.

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For frequencies above 100 kHz, special MOSFETs, so called CoolMOS or superjunction devices are in use. The disadvantage of these devices is their very high cost and their limited ruggedness and reliability. These sophisticated devices fight the physical limits of silicon by introducing very sophisticated n- and p-doped areas in the device structure.

International Rectifier's automotive product portfolio offers alternative solutions to address these problems at lower cost and with excellent switching performance. For example, the automotive DirectFET offers benchmark performance in fast switching applications up to 300 V and therefore can be used for power supply and converter applications in that range or for the low-voltage power stage of a high-voltage converter. The high-voltage area can be covered by the company's WARP-speed IGBTs, which offer high switching frequencies at better cost performance than typical high-voltage superjunction devices. IR's newest generation of automotive WARP speed IGBTs will address switching frequencies well above 100 kHz and therefore be well suited for high-power dc-dc converters in hybrid electric vehicles.

**4. Rugged MOSFETs with high avalanche capability.** Hard-switching applications often demand repetitive switching of the MOSFET by entering the avalanche mode where the breakdown voltage is basically exceeded and highly accelerated carriers at the breakdown-voltage level rush through the pn-junction area of the MOSFETs. Often called "hot carriers," these highly accelerated charges typically damage the gate oxide gradually. After a certain period of time or number of repetitive avalanche events, the MOSFETs suffer irreversible damage. The threshold voltage drifts and the MOSFET shows increasing leakage currents or even a total breakdown of the oxide, destroying the FET.

IR's proprietary MOSFETs are specially ruggedized and designed for reliable repetitive avalanche switching. Therefore, IR's automotive planar and Trench MOSFETs offer an extremely rugged design that eliminates the failure mode of hot-carrier injection and successive destruction of the gate oxides. This makes our devices well suited to hard switching of inductive loads, as is needed for the starter-generator used for the start-stop-function in mild or micro-hybrid vehicles. These devices offer a solderable-front-metal option to be used in bondwire-less DirectFET-style packages, which add improved switching performance to the silicon ruggedness.

**5. Rugged and robust driver ICs.** After all the power-switch improvements we need to emphasize there's also the need for durable driver chips to drive those power devices. To help system designers with the entire task of developing a power stage with the right driver IC, IR offers an extensive automotive driver IC portfolio that applies to a broad range of topologies and system requirements of state-of- the-art inverters, converters or power supplies.

Our proprietary automotive high- and low-voltage gate-driver ICs feature superior ruggedness and latch immunity. In the voltage range <75 V drivers based on a proprietary smart-power process allow very high current switching. In the range of 100 V to 1200 V, an extensive high-voltage junction isolated driver IC portfolio provides a negative-transient-voltage-spike safe-operating area (NTSOA) shown in Fig. 4.

The failure mode of state-of-the-art ICs is often the so-called latch-up due to large negative voltage spikes that occur when switching half bridges with high currents and inductive loads. International Rectifier's automotive driver ICs are rugged and latch up immune by design and therefore well suited to driving huge IGBTs with very high current density like the solderable-front-metal devices. If the system designer needs more drive current there is also a buffer IC available with up to 10 A of drive-current capability.

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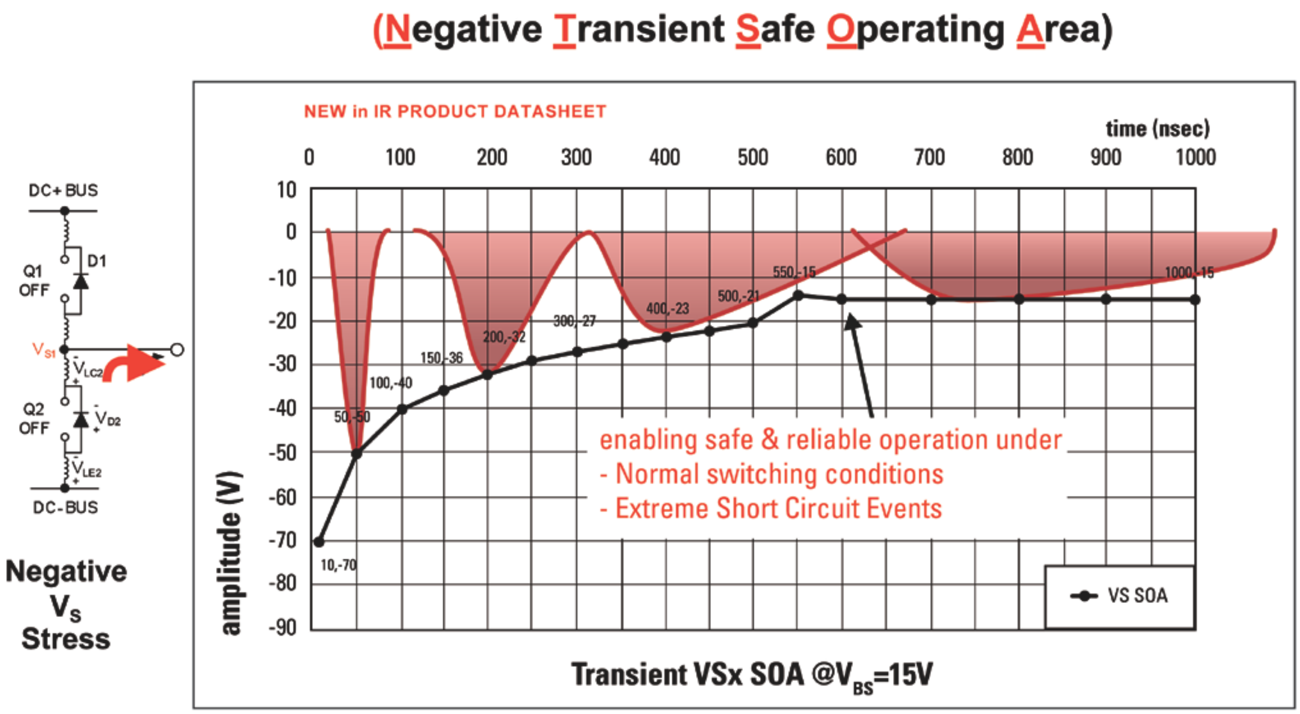


*Fig. 4. IR's automotive gate drivers are more rugged and robust due to process features and design, which provide absolute latch-robust control of even very large IGBTs that can generate big negative voltage spikes.*

The challenging requirements of high-power, high-current and high-voltage applications in hybrid electric vehicles can be solved and addressed with five key power management "ingredients." Optimized silicon switches together with advanced device packaging can provide solutions that address requirements for mechanical reliability, ruggedness, low inductivity and good EMI performance as well as cost-optimization of the entire system. When combined with rugged and reliable driver ICs that incorporate safety and protection features, these semiconductor devices enable car manufacturers and system suppliers to design very cost-effective and energy-efficient solutions for the affordable hybrid electric vehicle of tomorrow.

## About the Author

*Dr. Henning Hauenstein joined International Rectifier in June 2004 as program manager for the Automotive Systems Group, leading the development of IR's hybrid electric vehicle products and technologies. In December 2006, he was promoted to vice president of Automotive Marketing, a role in which Dr. Hauenstein was responsible for IR's automotive business strategy, business development and strategic marketing of IR's automotive product portfolio. In 2008, he extended his responsibilities to IR's industrial and appliance motion IC products. In his current position, Dr. Hauenstein is responsible for IR's Automotive Products Business Unit which was formed at the end of 2008 to focus five dedicated product lines under one single organization on the high-quality and enhanced reliability needs of the automotive market and its broad range of applications.*

*Prior to joining International Rectifier, Dr. Hauenstein held positions with increasing responsibilities from 1999 to 2004 in the product and technology development of the automotive supplier Robert Bosch GmbH. Most recently, he served as head of technology and strategic planning in Robert Bosch's Automotive Electronics Semiconductor & IC division. Dr. Hauenstein holds a doctorate in Natural Sciences with University Honors and a Diploma in Physics with University Honors from the University of Bayreuth, Germany.*

For further reading on power management in hybrid electric vehicles, see the How2Power Design Guide, select the Applications category and search the Automotive subcategory.

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