Designing power conversion systems with fewer, higher-voltage MOSFETs cuts component count, increases reliability and has little impact on the total area of the chips

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# Simplifying power conversion with **medium voltage SiC MOSFETs**

THE START of this decade heralded a new era for power electronics. Back then, commercial SiC power MOSFETs hit the market with operating voltages spanning 900 V to 1700 V. These rivals to the silicon incumbents attracted a great deal of interest from the outset, because they enable material and operating cost savings at the systems level, and improved efficiencies. These advantages have driven interest in the use of SiC MOSFETs for solar inverters, automotive charging systems, induction heating, welding power supplies, and a variety of additional power conversion applications.

Benefits of replacing silicon IGBTs with SiC MOSFETs result from the superior properties of the wide bandgap device. It slashes switching losses by a factor of 5 to 40; it does not suffer from a knee voltage, so conduction losses can be far lower; and it has a high performance body diode, so there is no need to pair it with an external antiparallel diode in applications requiring bi-directional conduction.

To increase the number of applications that SiC MOSFETs can serve, manufacturers of these devices have extended their capability to higher voltages. These efforts have included the development and evaluation of medium-voltage SiC switch devices, which span the 2.5 kV to 15 kV range, in traction applications.

Examples of this are Mitsubishi Electric's development of a 3.3kV SiC MOSFET power module for electric trains that yielded operating savings of 40 percent when power operation and regeneration modes were considered; and efforts by researchers at Fraunhofer ISE that explored the use of 10 kV SiC MOSFET switches for flexible photovoltaic power transmission from a 400 V panel to the grid. In the latter application, the switch from traditional transformers to SiC-based power conversion architectures increases the voltage for power transmission – and this has led to less copper cabling, higher efficiency, and greater flexibility in accommodating photovoltaic arrays with differing levels of power generation.

At Wolfspeed, a Cree Company, we have a rich history in the development and production of SiC MOSFETs. We were the first to bring these transistors to market,

 

Medium voltage (2.5 kV – 15 kV) SiC transistors are being explored for use in rail and in photovoltaic panel to grid power transmission. SiC transistors have demonstrated up to 40 percent operating savings in the rail market, and allow new approaches in photovoltaic panel to grid power distribution.

and during the intervening years we have improved device performance and expanded the range of blocking voltages. The 3.3 kV, 6.5 kV, and 10 kV SiC MOSFETs that we have developed are currently being evaluated by strategic leaders in rail, HVDC, grid-tied power distribution, and renewable energy grid storage applications. Their investigations offer important insights for engineers working with medium voltage applications above 100 kW and considering SiC devices for maximizing power density and driving down system complexity.

When engineers are designing these medium voltage power converters, one key decision that they face is whether to use higher voltage, lower current SiC MOSFETs connected in parallel, or lower voltage, higher current MOSFETs connected in series. Both approaches can deliver the desired voltage and power levels, and selecting the right way forward is more than just a matter of totting up the cost of the SiC die.

One of the merits of using medium-voltage SiC MOSFETs, rather than lower voltage variants, is that it enables simpler topologies with fewer levels

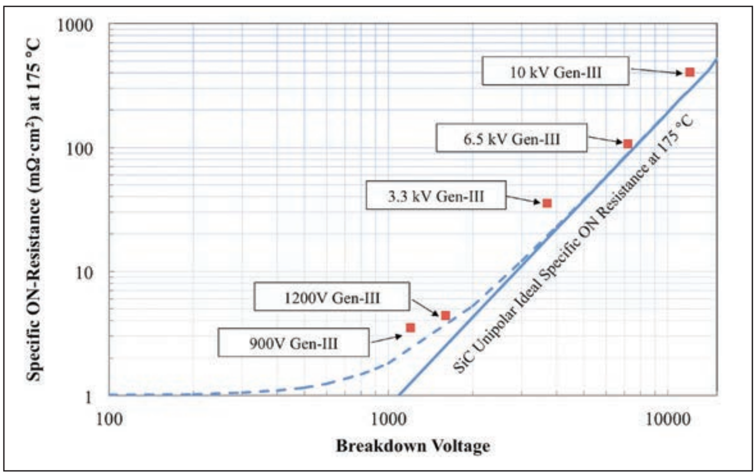


Figure 1: Examining the specific on-resistance at 175°C, the SiC unipolar ideal value is contrasted with the measured results of Wolfspeed's new Gen III SiC MOSFETs. Close agreement can be seen at higher voltages where the drift region resistance is dominant. The dashed line represents parasitic resistance of 1mΩ·cm² from ohmic contacts, channel resistance, etc. The data points represent the actual breakdown voltage of the device, while the labels represent the device voltage rating.

> For the body diode characteristics, which occur when a reverse bias gives rise to reverse current, the 10 kV SiC body diode produces the lowest forward drop. This advantage, which results from minority injected conductivity modulation in the drift region, highlights one of the benefits of selecting a single MOSFET operating at a higher voltage, rather than a string of lower voltage devices

and components. Cutting component count is very attractive, because it leads to higher reliability as there are fewer components that can fail. It is not just the number of MOSFETs that falls with this approach. The reliability of power converters also increases via fewer wirebonds inside a module, and a cut in the module, gate driver, and passive component count. Working with fewer components also simplifies design.

## Generation III

We are now developing our third-generation MOSFETs, which have voltages spanning 900 V to 15 kV. The merits of these transistors include a high reliability planar device structure and simple gate drive requirements. Another feature is the robust, low-reverse-recovery body diode, which enables significant system-level circuit design enhancements

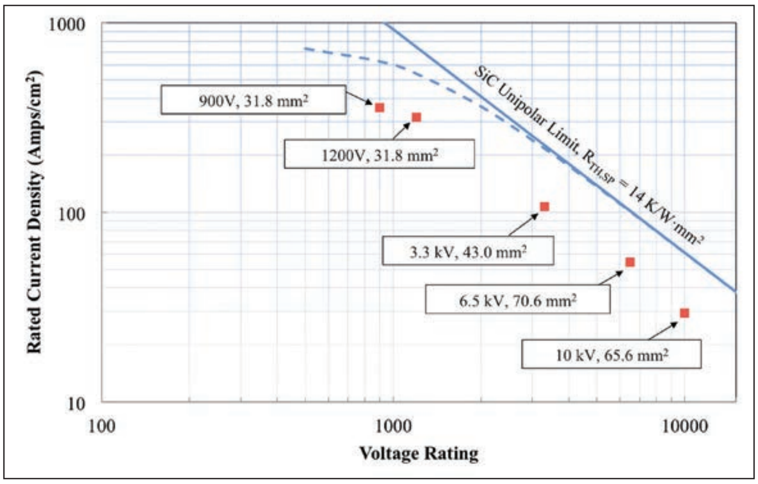


Figure 2: Rated current density of Wolfspeed Gen III SiC MOSFET chips in a typical module thermal environment, compared to rated breakdown voltage at 175°C, assuming a SiC unipolar limit of 14K/Wmm², with an AlSiC baseplate and 750 µm-thick AlN substrate. The dashed line represents the additional thermal limit from parasitic channel and contact resistance.

with regard to power density, cost, and reliability.

When engineers are faced with the task of selecting the most suitable SiC MOSFETs from our portfolio for a medium-voltage, high-power application, they must compare the measured performance, in terms of on-resistance as a function of breakdown voltage (see Figure 1). The downsides of a higher-voltage MOSFET are an overshoot of voltage during switching, and the additional voltage de-rating required to avoid device failure induced by terrestrial cosmic rays. In future, we will examine both of these limits in detail; for the purposes of this analysis, we will assume that SiC power MOSFETs, when properly designed and implemented in low-inductance modules, can operate at up to 80 percent of the rated voltage.

For lower voltage parts, parasitic resistances prevent the device from delivering its theoretical performance. These resistances come from the ohmic contacts, the channel, and the substrate. Together they contribute at least 1mΩ·cm², which is a fairly significant portion of total device resistance in MOSFETs rated below 1.7 kV.

To obtain a clearer picture of the expected MOSFET chip performance, the rated current density of our Gen III SiC MOSFET chips in a typical module thermal environment must be compared with the rated breakdown voltage at 175°C. We have undertaken this, measuring the SiC current density of each chip in a module environment (see Figure 2).

Armed with these figures for the rated current for the SiC MOSFET in a module environment we can obtain a figure of merit that is representative of the power density of each SiC MOSFET at 175°C (see Figure 3). Using this figure of merit – the product of rated current and rated voltage – we have, for the first time, been able to identify the amount of SiC needed, based on the selected MOSFET voltage rating.

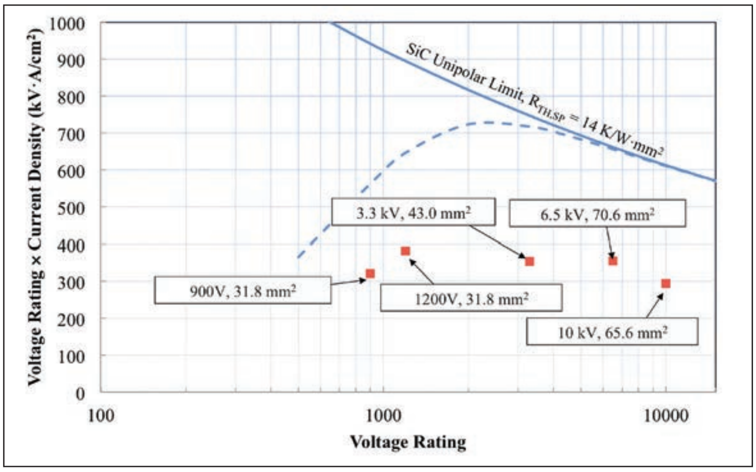


Figure 3: The measured power-density figure-of-merit of Wolfspeed Gen III SiC MOSFET chips in a typical module thermal environment compared to rated breakdown voltage at 175°C, assuming a SiC unipolar limit of 14 K/Wmm² with an AlSiC baseplate and 750 μm-thick AlN substrate. To implement a 10 kV switch, the amount of SiC used is relatively independent of the voltage rating of the chip between 1.2 kV and 6.5 kV. The dashed line represents the additional thermal limit from parasitic channel and contact resistance.

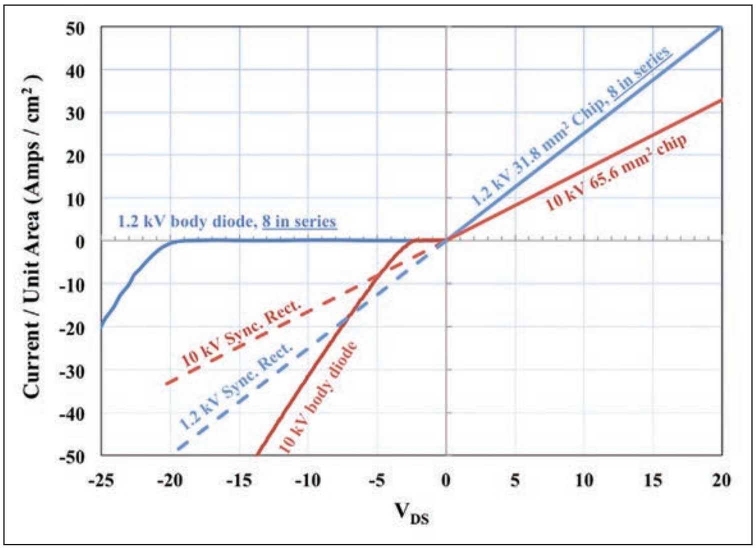


Figure 4: A comparison of the forward and reverse characteristics of eight series-connected 1.2 kV SiC MOSFETs and one single 10 kV SiC MOSFET chip at 175 °C. For the body diode characteristics (reverse bias, negative current flow), the 10 kV SiC body diode has the lowest forward drop due to minority injected conductivity modulation in the drift region.

This analysis is illuminating. One important insight is that for SiC MOSFETs spanning 900 V to 10 kV, the power density figure of merit remains very close to 350 kVA $cm^{-2}$ and varies by only 24 percent. And if we just consider the 1.2 kV, 3.3 kV, and 6.5 kV SiC MOSFETs, the achievable system power density per unit device area only varies by 7 percent. This is by no means an ideal limit, though. It should be possible to go beyond 400 kVA/$cm^2$ by building bigger die with a higher channel mobility, a reduced edge termination area and fewer defects.

So far, our analysis of SiC MOSFETs with different voltage ratings has been limited to considering only forward conduction. A rigorous assessment must go further, including anti-parallel current flow through the body diode and the channel of the MOSFET.

A key difference between the silicon IGBT and the SiC MOSFET is that the voltage range of the wide band gap device can utilize both the internal body diode and the channel of the MOSFET for anti-parallel current flow.

We have considered the impact of reverse characteristics when evaluating two options for a 10 kV switch: a single 10 kV SiC MOSFET; and eight, 1.2 kV SiC MOSFETs connected in series (see Figure 4). For the body diode characteristics, which occur when a reverse bias gives rise to reverse current, the 10 kV SiC body diode produces the lowest forward drop. This advantage, which results from minority injected conductivity modulation in the drift region, highlights one of the benefits of selecting a single MOSFET operating at a higher voltage, rather than a string of lower-voltage devices.

Our comparison of using SiC MOSFETs with different voltage ratings in medium-voltage power applications reveals that the total area of SiC material used is largely independent of voltage rating, giving designers the flexibility to choose the topology, part count, and system size that best suits their needs.

This makes higher rated SiC MOSFETs, such as 3.3 kV, 6.5 kV and 10 kV transistors, an attractive option, as they enable systems with simpler topologies, smaller part counts, and smaller physical sizes. On top of this, higher-voltage MOSFETs are favoured for their lower drop at reverse bias.

**Further reading**


"Silicon Carbide MOSFETs for Medium Voltage Megawatt Scale Systems," V. Pala *et. al*., International Conference on SiC and Related Materials, October 2015.

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J. Thoma *et. al*., "A Highly Efficient DC-DC-Converter for Medium-Voltage Applications," ENERGYCON 2014