SiC-Based Power Modules Cut Costs for Battery-Powered Vehicles

Demand for plug-in hybrid and all-electric vehicles is growing significantly, driven by, amongst other things, stricter emission regulations. However, current and future requirements call for further advances in efficiency and power density. Where Silicon plateaus in terms of performance, Silicon Carbide (SiC) presents a highly efficient alternative. **Laurent Beaurenaut, Principal Engineer, Infineon Technologies, Germany**

These vehicles are packed full of power electronics – most of which to date have usually been based on Silicon (Figure 1). In xEV drive trains, SiC circuits facilitate smaller chip dimensions with the same performance data offering advantages such as reduced switching losses and thus higher switching frequencies. Corresponding packaging technology renders more efficient, lighter and more compact power modules and discrete solutions possible compared to previous systems. Typical applications that benefit from SiC chips and optimised power modules include the main inverter, on-board charging electronics, boosters and DC/DC converters.

SiC components have been on the market for about two decades. However, their use in vehicles was limited for cost and partly for quality reasons. To date, wafer dimensions for SiC have generally been much smaller than for Silicon. The availability of high-quality 150 mm (6-inch) SiC wafers increases productivity in manufacturing SiC chips (Figure 2). Initially dominated by smaller, specialized companies, leading semiconductor companies now process SiC components on standard equipment with high outputs and high reliability. This results in promising cost developments for SiC. The latest generation of SiC trench MOSFETs also exhibits advances in gate oxide reliability, making them ideal for automotive applications.

Comparison of Silicon and Silicon Carbide

Compared to conventional Silicon-based high-voltage IGBTs or MOSFETs (> 600 V), SiC MOSFETs offer several advantages. For example, Infineon's 1200V SiC MOSFETs (CoolSiC) have lower gate charge and capacitance values than IGBTs, as well as minimal body diode reverse recovery losses. This results in switching losses, which are significantly lower compared to Silicon and also independent of the temperature (Figure 3). In addition, MOSFETs exhibit a resistance-like output characteristic, while in IGBTs this is similar to a diode. The threshold-free on-state characteristic results in smaller leakage losses in the part-load range.

The fundamental advantages not only make SiC MOSFETs ideal for operation at higher frequencies such as on-board charging circuits and DC/DC converters,

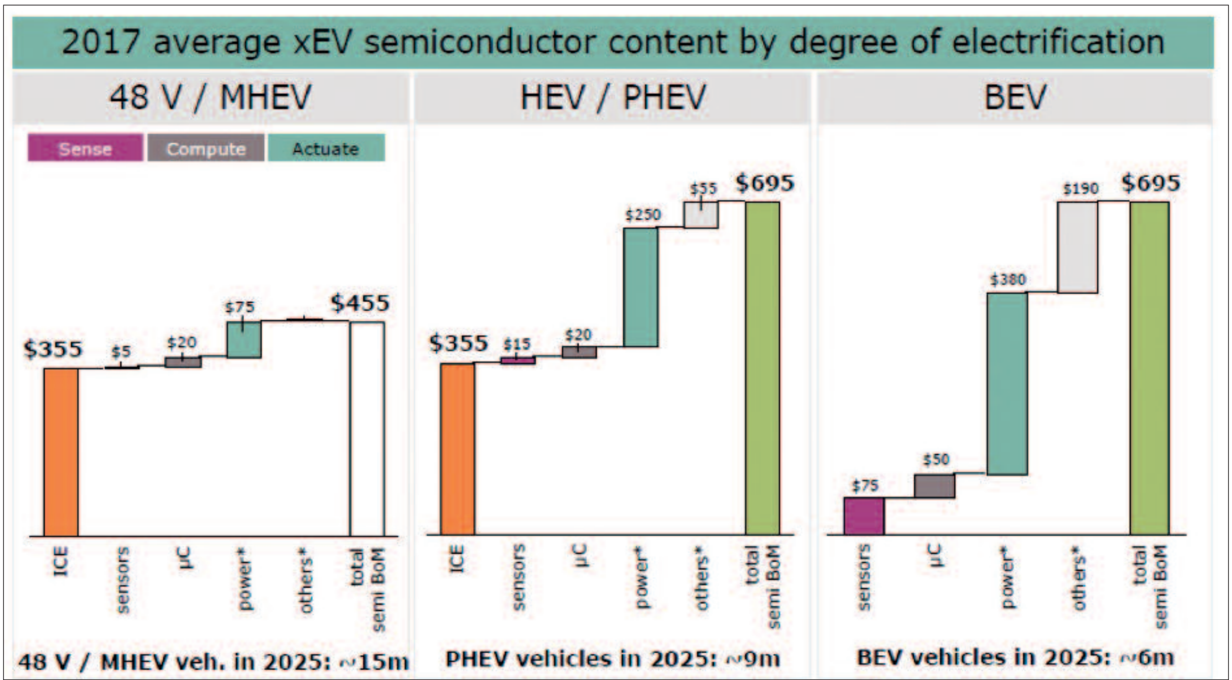

Figure 1: Average proportion of semiconductors in xEV applications depending on the degree of electrification

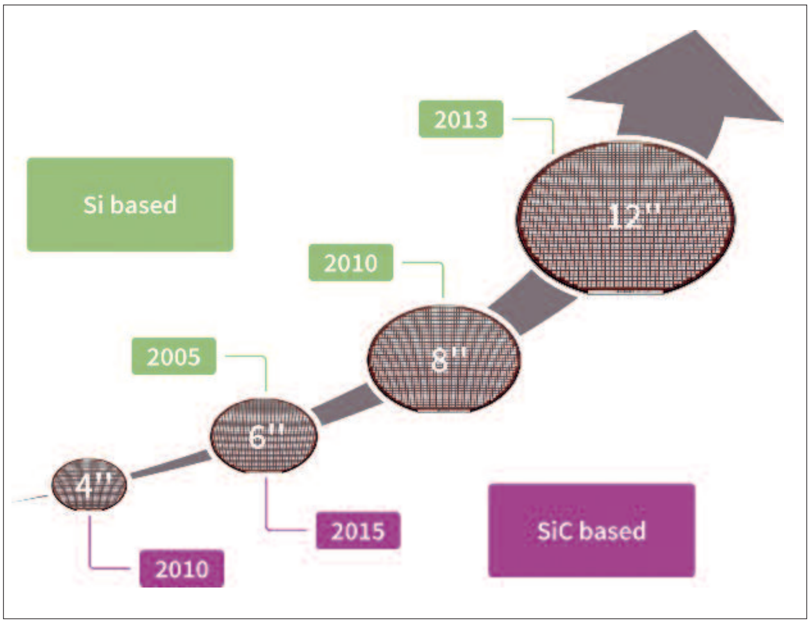

Figure 2: Larger wafers and improved processes reduce costs and increase reliability for SiC chips

but also for inverter applications, where switching frequencies below 20 kHz are typical. Here, the efficiency is determined to a very large extent by operation with low loads. Using SiC MOSFETs, it is possible, for example, to reduce the losses in inverters by up to two thirds under low or medium load.

Extremely compact and highly efficient inverters can be realised with SiC MOSFETs. Under comparable conditions, SiC MOSFETs significantly reduced the chip area compared to IGBT-based inverters. Thanks to the reduced chip losses, the efficiency has been improved for various driving scenarios, especially in city traffic with many acceleration phases.

In connection with the inverter efficiency, it is necessary to consider that the energy basically flows in two directions – from the battery to the wheel during the generation of the torque and back from the wheel to the battery during energy recovery (recuperation). Consequently, the efficiency of the inverter is very important for battery-powered electric vehicles (BEVs), because it has a direct impact on the range or the use of a smaller battery with the same range. Since the battery is an important cost factor, a 5 to 10 % reduction in battery cells can result in a significant cost reduction of over $800 in systems with more than 40 kWh of battery power.

Silicon does not support breakdown field strengths as high as SiC. As a result, a standard 1200 V IGBT exhibits significantly more losses than its counterpart in the 600 V class. On the other hand, a 1200V SiC MOSFET allows very efficient operation at higher battery voltage in the range of 850 V. SiC is therefore ideally suited for architectures that also enable fast-charging applications. With the infrastructure currently under development, an 80 kWh battery can be charged to 80 % in just 15 minutes. An important aspect for the implementation of electromobility and ensuring customer satisfaction.

Optimized power modules

In order to make the best possible use of the performance of the SiC chips, a correspondingly optimized packaging technology for the power modules is also required. SiC facilitates better energy efficiency. However, this not only requires

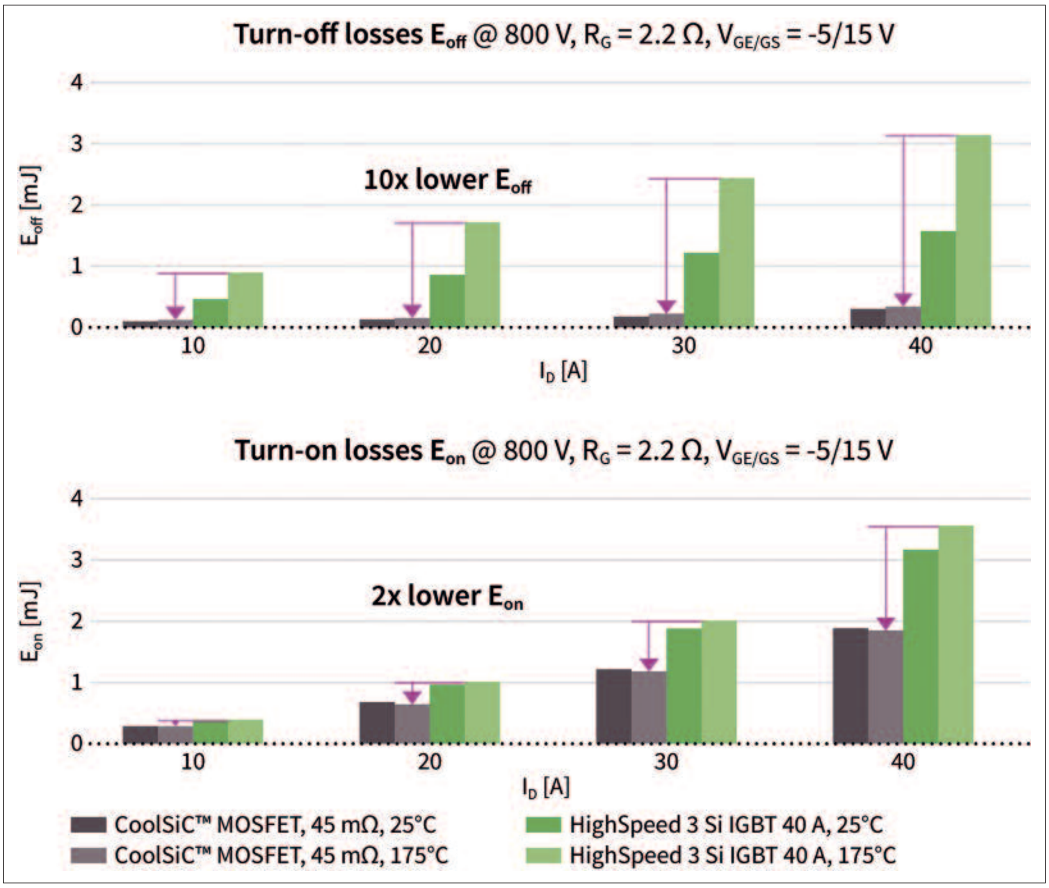

Figure 3: Comparison of switching losses between CoolSiC MOSFETs and silicon IGBTs

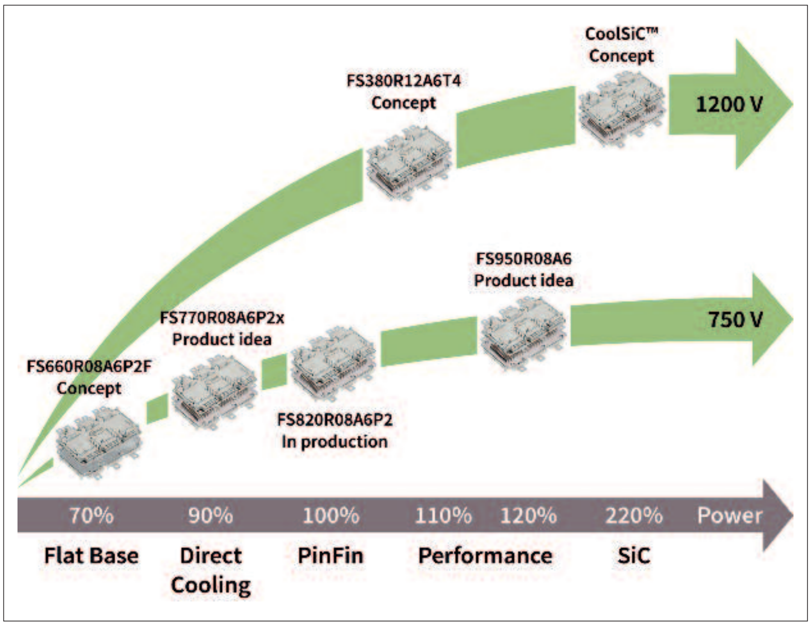

Figure 4: The HybridPACK Drive power module has a modular design and can be easily scaled

improved packaging materials, but also the consideration of higher thermal resistances for smaller chips. Smaller chips also cause higher current densities and a greater risk of thermo-mechanical deformation. To fully exploit the performance of the SiC MOSFETs, packaging with the lowest possible leakage inductance is required. Consequently, new innovative packaging concepts for power modules are required. Examples include the optimized modules of the HybridPACK Drive family and packaging concepts with double-sided cooling, such as HybridPACK DSC modules. This makes it possible to develop inverter designs with very high power density.

HybridPACK drive

When developing the HybridPACK Drive (HPDrive) power module for use in electric and hybrid vehicles, it was necessary to combine technical and application-related requirements. These include elements as diverse as optimized costs, high efficiency, power density, current carrying capacity for starting torques and service life due to thermal cycling. It has been shown how a fully integrated development approach allows all the individual components of a power module to be designed in such a way that the application requirements are met to optimum effect. The higher rated voltage of the chip and the lower inductance of the module allow operation at higher working voltages and switching edges. The higher temperature load capacity, the improved chip bonding technology and materials with lower losses allow a higher current carrying capacity and thus a higher starting torque of the drive motor. Altogether, the smaller module size with reduced chip area, lower losses and the use of the latest mass production techniques help to reduce system costs.

A HybridPACK Drive module with pressfit terminals and the latest IGBT technology for automotive (EDT2) is about 20 % smaller than the comparable equivalent of the HybridPACK2 family, with the same performance. The HybridPACK Drive product line is a scalable platform with various options for power connections, IGBT and MOSFET technologies, as well as the thermal stack. The family was modular from the outset. The modular concept begins with the terminal taps, which facilitate either a quick welding process or screw-bolt joint for the cable connection. A 'long tap' version is also available for implementing phase current sensors.

HybridPACK Drive modules are designed to minimize development effort for inverter manufacturers depending on the application. It is thus possible to either reduce or increase the output power by replacing the base plate or the thermal stacks, while the Silicon part remains unchanged. Various base plates (flat, direct cooling and pin-fin) as well as various ceramic substrates are available for this purpose. The performance can however also be scaled by retaining the electronics (driver board and DC link capacitor) and the inverter design, but adapting the cooling structure. If you take e.g. the FS820R08A6P2 module with 750 V IGBTs, pin-fin structure and standard ceramics as a 100 % reference, this produces a scaling bandwidth for performance of 70 to 120 % (Figure 4).

For even higher powers, 1200 V technologies are also available for the HybridPACK Drive. First of all with 1200 V IGBTs and improved ceramics and then in future also with SiC MOSFETs (CoolSiC). With the introduction of SiC or CoolSiC, not only can the performance of an inverter be virtually doubled, but it can also reduce system costs in terms of the battery and smaller components.

Combining SiC and HybridPACK drive

The first on-board charging systems with SiC diodes are now coming onto the market. However, the high-voltage battery will continue also in future to be the most expensive part for hybrid and electric drive systems, considering that vehicles that are solely battery powered (BEVs) need a battery capacity of up to 100 kWh for ranges of 400 km and more. In this case, a high-efficiency inverter with lower losses permits better battery utilization and thus longer range.

To compare the efficiency of silicon and SiC based inverters, different driving scenarios such as NEDC (New European Driving Cycle), WLTP (Worldwide Harmonized Light Vehicles Test Procedure) and realistic Artemis simulations were investigated (Figure 5). This showed that a

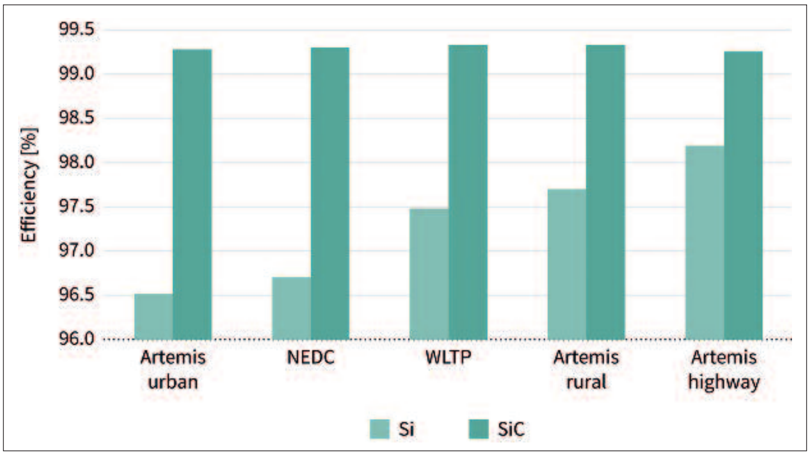

Figure 5: Efficiency comparison for various inverter implementations based on a HybridPACK module (Si and SiC) and different driving profiles

SiC-based inverter can achieve an efficiency of over 99 % and what's more for all scenarios. If the recovery is also taken into account, a SiC inverter can extend the range for BEVs by 5 to 10 %. This efficiency increase is based in particular on the faster switching of the SiC MOSFETs with up to 80 % lower switching losses compared to the IGBTs. Even if this potential cannot yet be fully exploited, due to EMC criteria and parasitic effects, the elimination of recovery losses and current-tail effects at shutdown alone will significantly reduce dynamic losses. In addition, SiC offers a resistance-like output characteristic. This makes these components ideal for low-load conditions that make up much of inverter operation. An inverter thus operates more than 80 % during active operation with loads of 20 % or less.

SiC-based inverters are expected to be used in premium BEV platforms that require more than 200 kW of power and 850 V system voltages to support fast charging. SiC technology offers decisive advantages precisely in this area. To facilitate the implementation of SiC inverters, Infineon is developing power modules based entirely on SiC on the basis of the scalable HybridPACK Drive package (Figure 6). These modules cover a power range up to 300 kW.

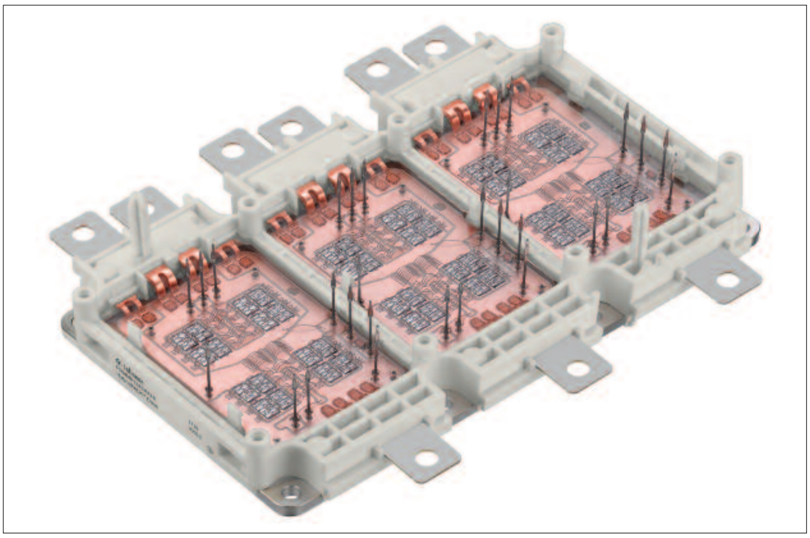

Figure 6: **HybridPACK Drive based on CoolSiC allows the performance to be doubled**

Conclusion

More and more OEMs and automakers are turning to SiC for future development. With 1200V CoolSiC MOSFETs, Infineon has demonstrated new capabilities in terms of efficiency and power density, coupled with innovative packaging technology, corresponding gate drivers and extensive automotive expertise. This means that in future xEV vehicles and other automotive applications will be able to take advantage of SiC. With the integration or combination of SiC MOSFETs and/or CoolSiC and the optimised, scalable HybridPACK power module package, inverter performance can be doubled compared to a corresponding module with 1200V Si IGBTs whilst reducing system cost.