Semiconductors in Hybrid Drives Applications

With the upcoming importance of energy saving in future cars as well as CO_2 reduction, today's hybrid cars show the potential of reaching more efficiency in automotive applications. Besides the power semiconductor devices used for the main inverter, additional electronic components will be needed in future vehicles. The structure and function of the different hybrid drive components, as well as used semiconductors and the latest IGBT, MOSFET and SiC technologies, will be described below. According to the special needs of hybrid drives applications, future trends like increased junction temperature or new interconnection technologies will be illustrated. **Ingo Graf and Mark Nils Münzer, Infineon Technologies Warstein and Munich, Germany**

Depending on the functionality and power range, three systems (Micro-Hybrid, Mild-Hybrid and Full-Hybrid) are implemented in available cars. The level of hybridization has direct impact on fuel consumption. Figure 1 shows an overview on the implemented functionalities and potential fuel savings in hybrid cars.

Hybrid system architecture

Besides the combustion engine, a minimum of one additional electric motor/generator is integrated in Mild- and Full hybrid cars. Here, the electrical motor is driven by battery voltages in the range 120 to 400V. An additional high voltage battery (e.g. new lithium ion) is implemented as well. For exchanging energy between the 14VDC power net and the DC high voltage (HV) power net, a DC/DC converter is used. Steering the electric motor is realised by using a DC/AC inverter. An optional additional DC/DC boost converter can be used to increase the battery voltage. The hybrid system allows additional auxillary drives realised by additional inverters (DC/AC). New opportunities like ventilating and air conditioning (HVAC), power steering or oil pumps will be possible (see Figure 2).

Typically, the inverter is realised by six IGBT switches, each with antiparallel diode in power modules well known from industrial and traction applications. The switching frequency is in the range of 8 to 10kHz.

For DC/DC converters different configurations can be used. H-bridge and half-bridge topologies can be found, as well as configurations with active (MOSFET, CoolMOS, IGBT) and passive components (diodes). The optional booster is often realised as a half-bridge with two switches (for 600V IGBT/diode or 600V CoolMOS).

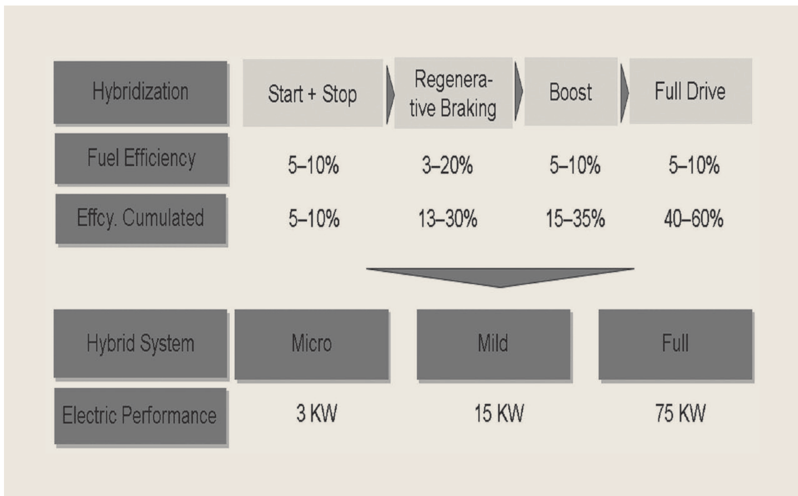

Figure 1: **Level of hybridisation in cars**

An optimised DC/DC behaviour with low voltage ripple can be reached by increasing the switching frequency up to 100kHz. Therefore, low power DC/DC converter topologies are realised by MOSFET devices.

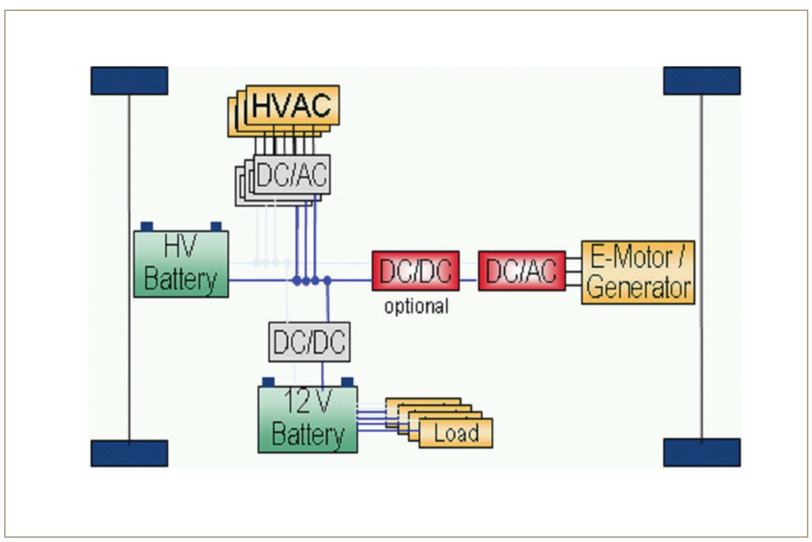

Figure 2: **System architecture of a hybrid vehicle**

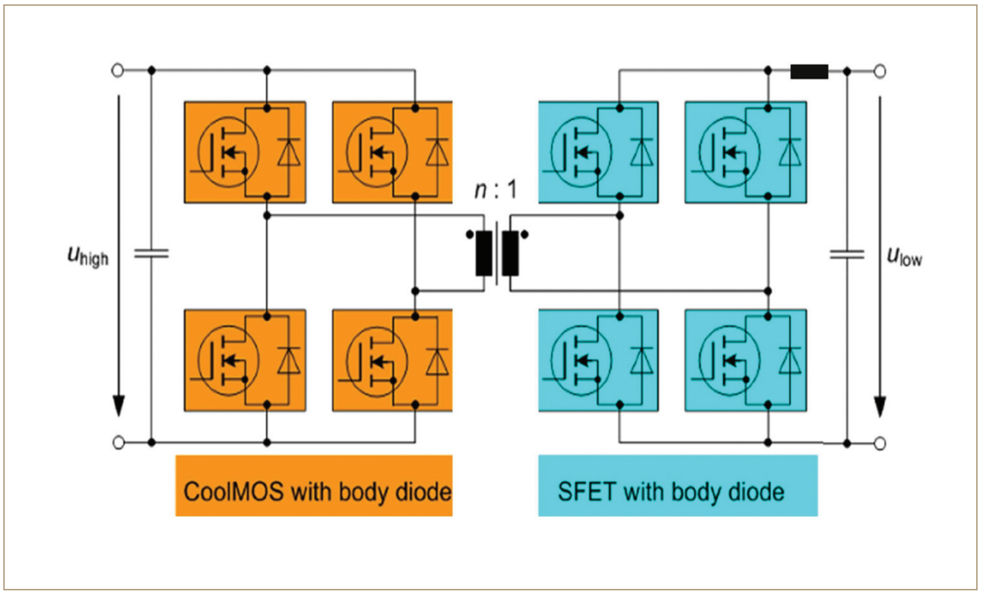

Figure 3: DC/DC configuration (dual active bridge)

The switching losses of MOSFETs are much lower compared to IGBTs in this operation mode. For example, the DC/DC converter (between 14V and HV power net) can be realised with two H-bridges (dual active bridge). The low voltage side consists of e.g. 40V MOSFETs and the HV-side by e.g. 600V CoolMOS devices (Figure 3). All inverter and converter configurations request appropriate driver ICs and driver stages for an optimised switching behaviour of the used IGBTs and MOSFETs.

Requirements for HEV power electronics

Besides cost and performance, quality is a major topic for HEV power electronics. Although expected quality level and lifetime are same for all components, the environmental stress that determines the requirements for each component might be very different. As with most automotive components, the requirements for power semiconductors vary between different mounting places and cooling conditions. A power semiconductor module that is mounted on a forced air cooled heatsink in the trunk will experience less vibration and thermal cycles over the expected lifetime than a transmission mounted power semiconductor module that is cooled by the transmission oil.

In terms of thermal resistance, liquid cooled systems show significantly better behaviour than air cooled systems. Due to the low losses, mild hybrid systems can still be cooled with forced air cooling. Full hybrid systems need liquid cooling to dissipate the power (see Figure 4).

To improve the efficiency of a hybrid drive, it is important to reduce the losses in the power semiconductor. MOSFET and IGBT are the predominant power semiconductors in HEV applications. Due to the uni-polar characteristic, the switching losses of a MOSFET are significantly lower than those of an IGBT. As a result, applications with high switching frequency (>100kHz) are the domain of MOSFETs, while applications with low switching frequencies (<10kHz) are typically dominated by IGBTs. The unipolar characteristic also leads to a

	Trunk mounted with forced air cooling	Engine compartment with seperate liquid cooling	Engine mounted with engine coolant	Transmission mounted with transmission coolant
Ambient temp.	-40 - 85°C	-40 - 105°C	-40 - 105°C	-40 - 140°C
Coolant temp.	-40 - 65°C	-40 - 85°C	-40 - 125°C	-40 - 150°C
Thermal cycles	Medium	High	High	Very high
Power cycles	Medium	High	High	High
Vibration	5g	10g	10g	20g
Shock	50g	100g	100g	400g

Figure 4: Requirements for different mounting and cooling conditions of power electronics

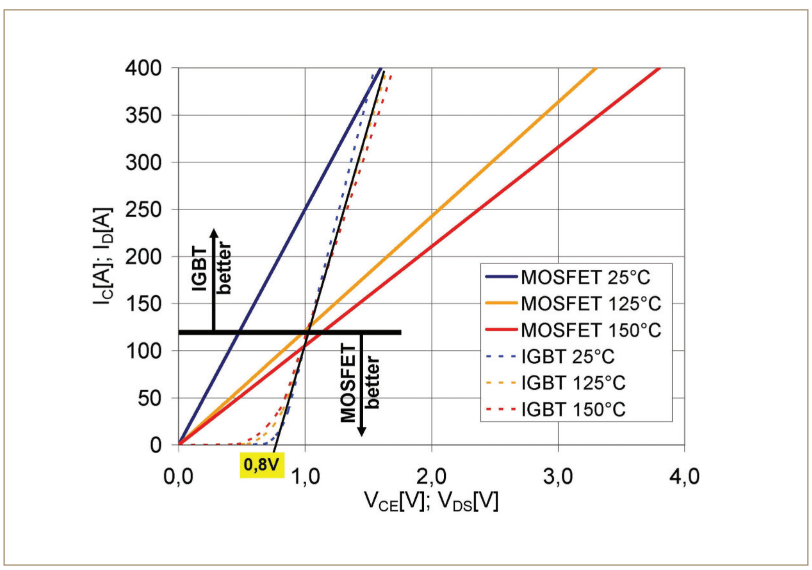

Figure 5: Conduction losses of same area 600V IGBT/Diode and 250V Trench MOSFET

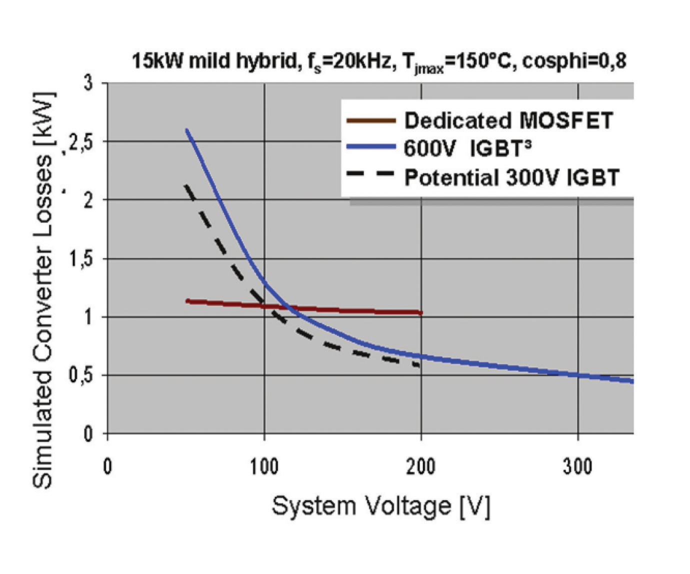

Figure 6: Converter losses versus system voltage for different chip technologies

resistive transfer characteristic. In contrast, the transfer characteristic of the IGBT shows a threshold voltage of about 0.8V due to the pn junction at the back side of the IGBT. Only above this voltage can a resistive characteristic be observed (see Figure 5). While the resistive part scales with the blocking voltage the threshold is independent. Therefore, IGBTs are less suitable for low voltage applications then MOSFETs.

As can be seen in Figure 6 the 600V IGBT is superior to a dedicated MOSFET as long as the system voltage is higher than ~120V. To show the potential of future IGBT devices with lower breakdown voltages, the results of a 300V IGBT have been estimated and included in this figure.

Besides the influence of the losses on the efficiency of a hybrid drive, they also directly influence the cost of the system, especially the cooling and necessary silicon area. The losses generated in the silicon heat up the device. To keep the chip temperature below the maximum allowable junction temperature a significant effort in cooling has to be made. Chip sizes and thus, costs, could be reduced at improved electrical characteristics (overall losses and robustness) step by step, and as a result, the inverter efficiency rises at more compact sizes.

One essential key topic was the development from the vertical IGBT device structure (PT) to the current

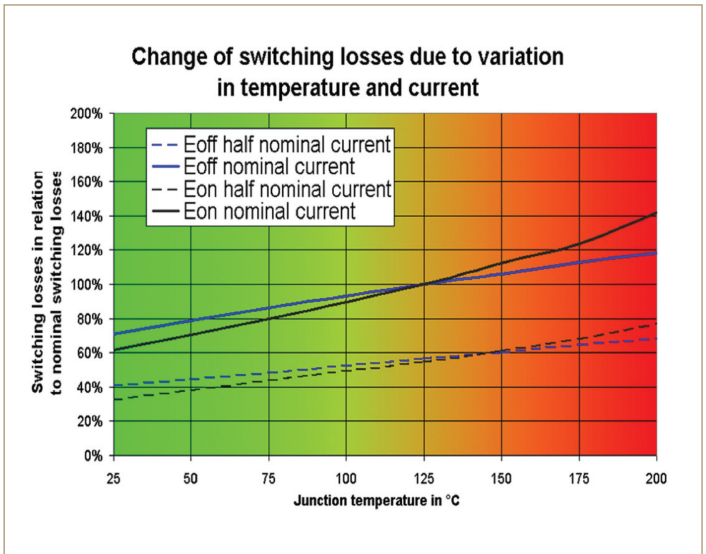

Figure 7: Influence of temperature on switching losses

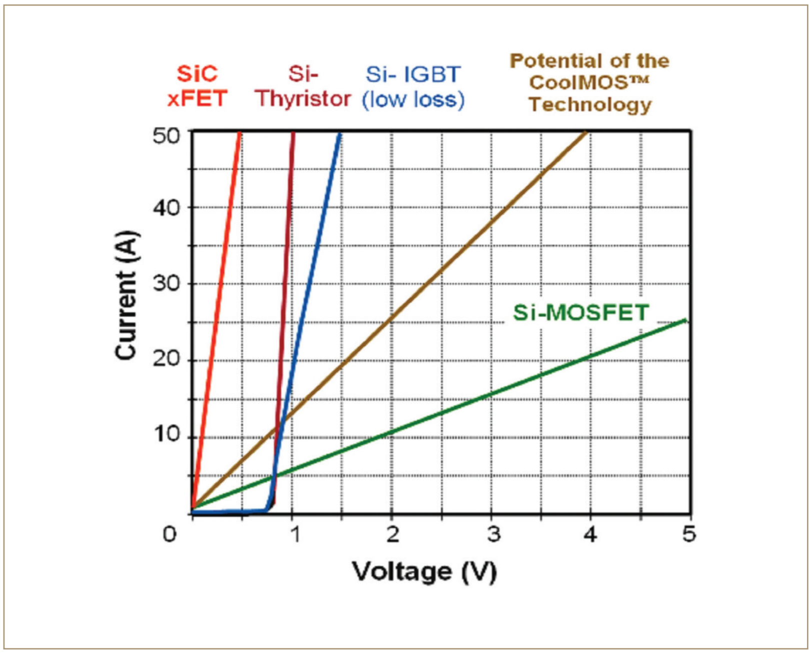

Figure 8: **Expansion of virtually loss-less switching voltage range by unipolar SiC switches**

Field Stop device structure (FS), resulting in a continuous reduction of the active device thickness. This is very important as on-state as well as switching losses directly correlate to the device thickness. Thus, a leading edge process technology for ultra-thin IGBT and diode silicon wafers is one key factor. Modern 600V IGBTs and free-wheeling diodes are now in production with only 70µm thickness.

High temperature capability

To minimise the cooling effort, it is necessary to increase the maximum allowable junction temperature. With the introduction of 600V IGBT³, the allowable junction temperature has been raised by 25°C to 150°C operational and 175°C maximum. As can be seen in Figure 4, this increase can be fully utilised as the conduction losses are almost independent of the temperature. Also, the switching losses are only slightly increased when going to higher temperatures (see Figure 7).

Also, during switching as well as short circuit tests, the IGBT³ showed its robustness at a junction temperature of 200°C. These results show that, in general, an increase of the junction temperature for future IGBT generations is possible. This will be essential to meet the future needs of power electronics especially in hybrid vehicles.

Talking about the future of power semiconductors, of course silicon carbide (SiC) has to be mentioned, as this material shows many advantages compared to silicon - 10 times higher electrical breakdown field, 3 times better thermal conductivity and a high temperature operation well beyond 200°C. In some high performance industrial applications like PFC (power factor correction), it already makes sense and commercially available 600V silicon carbide Schottky diodes do their work. Higher blocking pin diodes are also in the development phase. For silicon carbide switches JFET and MOSFET designs are under investigation. Figure 8 shows the potential of such semiconductors compared to existing technologies. The conduction losses of an SiC-xFET could decreased by a factor 3 compared to a low loss Si-IGBT. Due to the large band gap of 3.2eV, there is no development of a SiC-IGBT. As a first

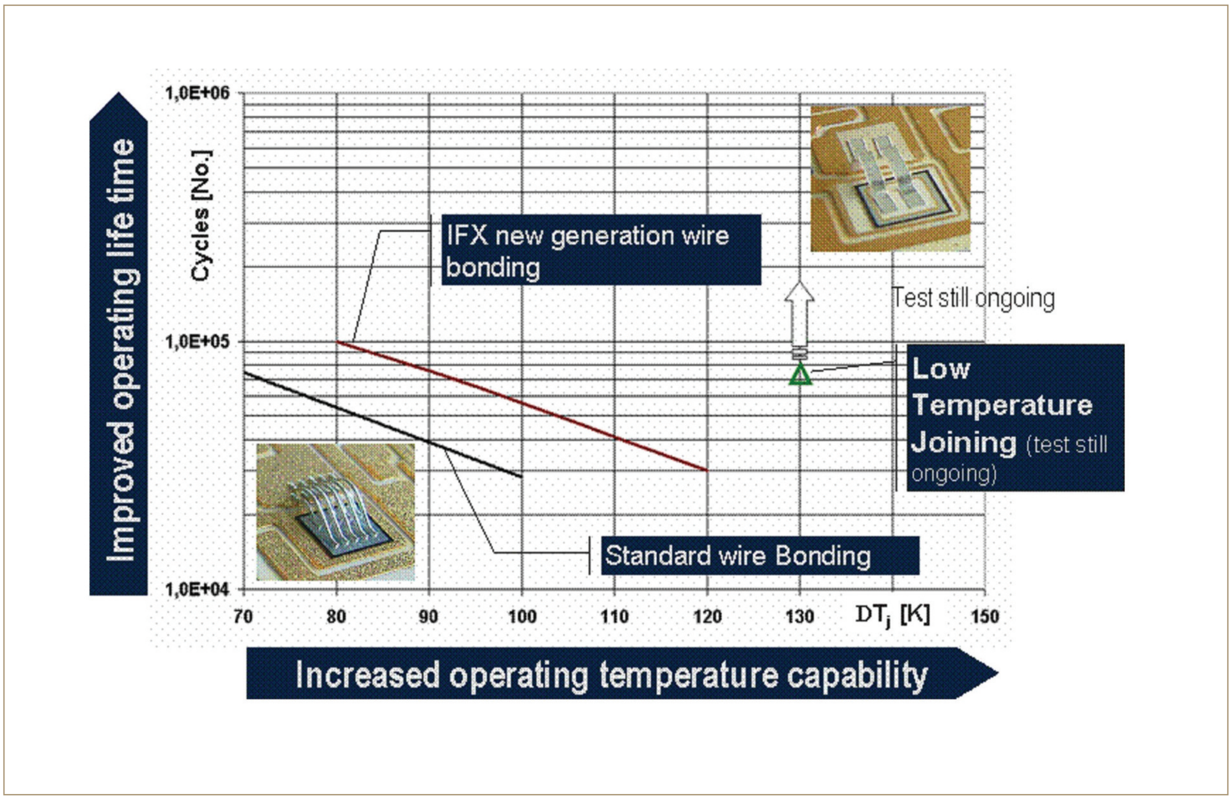

Figure 9: **Improvement of power cycling as a result of new interconnection technologies**

step, maybe the combination of a Si IGBT switch and a SiC Schottky diode will become attractive in hybrid car applications.

New interconnection technologies

Today, power semiconductor modules usually contain several IGBTs and diodes, which are soldered onto a metallised ceramic substrate. To connect the top side of the chips, wire bonding is state of the art. Multiple substrates are connected to a baseplate by use of soft-solder joints

Changing the maximum allowable junction temperature of the power semiconductor will directly change the thermal stress on the interconnection of the chip surface. A typical wear-out effect at the chip surface is the wire bond lift off. To test this interconnection, power cycling tests are performed. The number of cycles that a device survives is related to the temperature swing, the maximum temperature and the slopes. For the introduction of a maximum junction temperature of 175°C, the wire bonding process has already been improved from standard wire bonding to the IFX new generation wire bonding (see Figure 9). For future designs results of the low temperature joining process are promising. As can be seen the tests were still ongoing after 70000 cycles with a temperature swing of 130°C.

Over the lifetime of DCB modules, the layers are prone to recurring mechanical stress, due to the ongoing thermal cycles. Caused by the current flow in the semiconductor and the resulting heat-up, the materials used, such as copper, ceramics, silicon and aluminium expand with their different coefficients of expansion. This may lead to premature solder fatigue between the DCB substrate and the baseplate. The result is delamination of the solder layer and the increase of the thermal resistance caused by this. Finally, the component fails due to overheating.

For industrial applications modules with a standard DCB (Al_2O_3) in conjunction with a copper baseplate are usually used, as the requirements for thermal cycling capability are much lower here than in traction applications for example. For these, a combination of materials is often used consisting of an AlN DCB and an AlSiC baseplate.

An important qualification test for semiconductor modules is the so-called thermal shock test (TST). In this two- chamber test, the module is permanently exposed to temperature fluctuations of -40 to 125°C (or 150°C) and from 125°C (or 150°C) to -40°C. After the test with a predetermined number of cycles the degree of solder layer delamination between baseplate and DCB is evaluated. Power semiconductors for hybrid drives bear requirements of up to 1000 cycles of thermal shock. This requirement cannot possibly be achieved with a standard DCB module construction. One solution would be the use of the material combination mentioned above – AlN DCB with AlSiC baseplate.

This approach, however, results in added material cost and is suitable primarily where the heatsink temperature is already at a very high level. Considering the temperature fluctuations and number of required thermal cycles during the lifetime, a cost optimised solution has to be found for the power semiconductor concept. One solution is the use of a so-called 'improved' Al_2O_3-DCB in conjunction with a copper baseplate. This combination of materials is mainly suitable for mild hybrid systems and some full hybrid systems.

When designing the power semiconductor module, particular consideration needs to be given to the load profile during the lifetime of the hybrid vehicle. Once the required profiles are available detailed in passive temperature fluctuations and current profiles, a suitable combination of materials (DCB/baseplate) can be determined.

Conclusion

The special requirements in hybrid cars have deep impact on the right choice of semiconductor solutions. The development of new power semiconductors and interconnection technologies can help to save costs by a reduction of losses and an increase of the maximum junction temperature. The development of new chip generations will yield higher power densities and reduced chip areas at the same time.