Power Modules for Electric and Hybrid Vehicles

No baseplate ensures superior thermal cycling capability

The urgent call for the reduction of CO_2 emissions has led major automobile manufacturers to work on the development of new solutions for electric and hybrid drive vehicles. In order to develop a power semiconductor module for these applications, new solutions for module integration and packaging technology are needed. Conflicting requirements, i.e. maximum power density, efficiency and reliability at low costs, can only be achieved, however, if the right choice of components is made, innovative solutions and technology are developed, and thermal and electrical properties optimized.

By Dr. Arendt Wintrich, Application Manager SEMIKRON

The SKiM® power module family (Semikron integrated Module) is the latest generation of ultra compact, baseplate-less pressure contact modules from Semikron. Instead of soldering the DCB, the ceramic substrate required for isolation, to the copper baseplate, the connection to the heat sink is by way of pressure. Pressure points positioned directly beside every chip guarantees that the DCB is connected evenly. The fact that no baseplate is used ensures superior thermal cycling capability and low thermal resistance. Figure 1 shows a cross-section of the module case, the pressure contact system and the spring contacts for the gate connections.

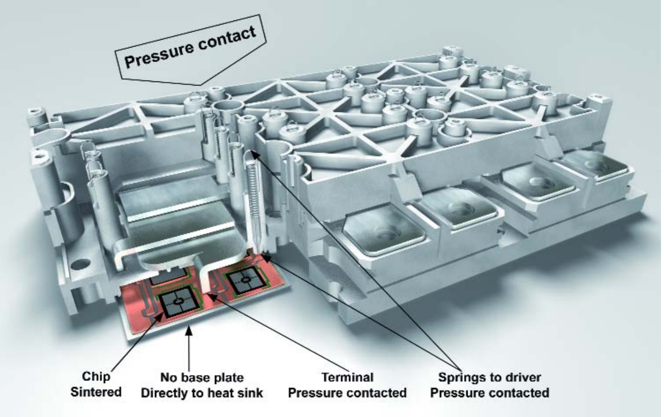

Figure 1: SKiM modules fulfil the requirements for inverters in electric and hybrid vehicles

The electric circuit is a 3-phase inverter circuit. Each half-bridge has its own DC connections and its own temperature sensor. The gate connections for the IGBT's are made using spring contacts. The PCB for the gate driver is not soldered onto the module but is screwed to the module from above. The spring contacts guarantee reliable connection, even in the case of strong thermal cycling and vibrations.

The components are designed for an inverter output of between 30kW and 150kW, depending on the operating and cooling conditions. Table 1 shows the component parameters and typical power inverter output currents.

	SKiM 63	SKiM 93	
$R_{\text{thjs IGBT}}$	0,14	0,095	K/W
$R_{\text{thjs Diode}}$	0,27	0,18	K/W
$I_{\text{C nom, 600V}}$	600	900	A
$I_{\text{C nom, 1200V}}$	300	450	A
$I_{\text{RMS, 600V}}^{1)}$	280	410	A
$I_{\text{RMS, 1200V}}^{2)}$	165	250	A

Table 1: Main module parameters

Busbar design

An excellent and reliable module solution is the design for the internal load connections (Figure 2). The load connections perform various tasks inside the module and have been optimised with a view to these different tasks:

Solder-free, low-inductance connection between the main terminals and the chips
High current carrying capability and low losses for high inverter currents
Symmetric current path, which provides good current distribution between the parallel chips
Pressure points close to the chips provides low thermal resistance.

The sandwich structure with parallel current paths to every single chip guarantees an extremely low internal inductance value. The inductance L_{CE} between the screw connections of the DC connections and the AC connection is less than 10nH, with an overall inductance from plus to minus of less than 20nH.

An FEM analysis showed that the majority of the inductance is caused by the distance between the end parts of the +/-DC connections. With a FEM simulation the design was optimized and the inductance could be reduced by 30% (-10nH). Further improvement is not viable since the sandwich structure cannot be used here in order to provide the mandatory air and creepage distances. The only way to achieve a further reduction in inductance is to use several parallel connections to the DC link circuit.

The benefit of this design for users is, among other things, the low internal switching overvoltage, which allows for operation with relatively high DC link voltages and safe turn-off, even in the case of a short circuit. Smooth switching processes with no oscillations guarantee low switching losses and low interference emissions.

Improved semiconductors allow for increasingly higher power densities in small cases. The rated chip current of the 600V SKiM 93 is 900A, which is almost twice as high as that of standard modules. This current value also exceeds the limit for the permissible current capability of the main terminals of existing IGBT modules. The wide and thick copper sheet used in the SKiM modules has a total resistance $r_{cc'-ee'}$ including contact resistance of just 300μΩ which is only half the value of standard modules. High contact forces guarantee a low contact resistance. The losses that occur nevertheless are quickly dissipated to the cooling DCB surface and heat sink by the many short contact points.

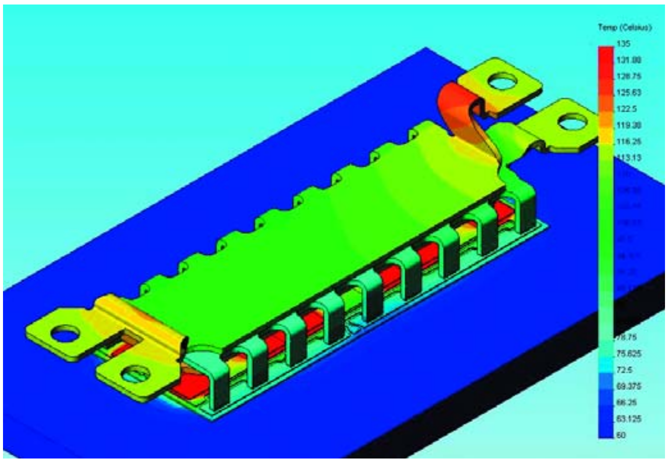

Figure 2: Main terminals with “sandwich” design and numerous contact feet - FEM simulation of terminal temperatures for an output current of 600Arms

In an inverter, the highest current passes through the AC terminal. For this reason, the AC terminal is positioned at the lowest point in the sandwich construction, as this point has the best cooling properties. With a heat sink temperature of 70°C, the module is designed for an effective current at the AC output of 600A. This value is far higher than the expected continuous current (see Table 1). Even with semiconductor losses of about 2000W, the terminal temperature can be kept under 125°C (see Figure 2).

DCB layout

The DCB design and the chip position have an important influence on the switching behaviour and the thermal resistance of the power semiconductors. Asymmetric component design can easily cause a non-homogenous distribution of current of 10% or more. The total output current then has to be limited to the component with the biggest power dissipation.

Voltage drops across parasitic inductances can be responsible for different switching speed and oscillations between parallel chips. To ensure smooth and synchronous switching the inductances have to be as small as possible and, more importantly, have to have the same influence on all of the semiconductor chips. A design featuring building blocks with 2 IGBT’s on the left and right and a freewheeling diode in the centre guarantees this. The path for current commutation between IGBT and diode is as short as possible and has the same length for the top and bottom switch of a converter half bridge (see Figure 3).

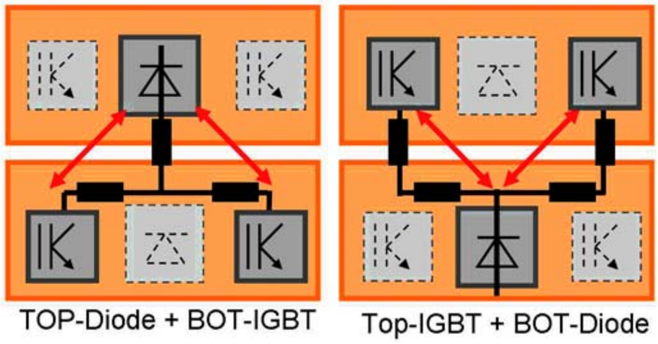

Figure 3: Current commutation path between IGBT and freewheeling diode for the top and bottom switch

Figure 4 shows the switching behaviour of a SKiM 63 module at 600A and 900V DC. Switching losses, overvoltage and di/dt are virtually identical for the top and bottom IGBT. This is not always the case; in fact, in most cases there are clear differences caused by the different parasitic inductances in the currents paths.

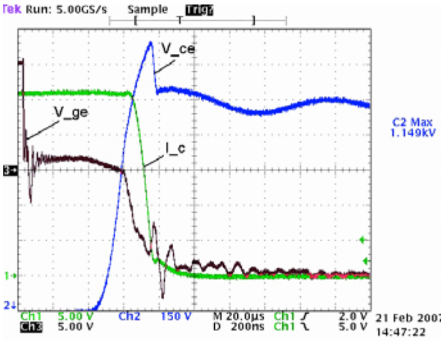

Figure 4: Turn-off of bottom IGBT at double the nominal current I_c 600A (green), V_{CE} (blue), V_{GE} (brown) @ 900V_{DC}, 125°C

Similarly, to ensure that components are used to their full capacity, good current distribution is needed between the parallel chips. The impedance of the +DC to –DC current path and the influence that the main current has on the gate circuit must be the same for all of the chips.

The first condition is met by the sandwich busbar system. The magnetic field barely changes for current commutation from + to –DC. The inductances of the main terminals are coupled and are therefore negligible. The impedance is identical for all of the parallel chips.

The second requirement is also taken into consideration in the selected design. Even under dynamic conditions, all of the IGBT’s have the same gate emitter voltage. In the IGBT-diode-IGBT module, the voltage drops induced by di/dt cancel one another out, meaning that all of the transistors are affected by the voltage drop across the bond wires in the same way. The result is good current distribution, even in short-circuit conditions.

Thermal resistance Rth
Low conducting state voltages and maximum junction temperatures of 175°C allow for very high nominal currents. The nominal current density can be higher than 2A/mm². If the right chip size is selected, the optimum balance between nominal current, cooling requirements and costs can be achieved.

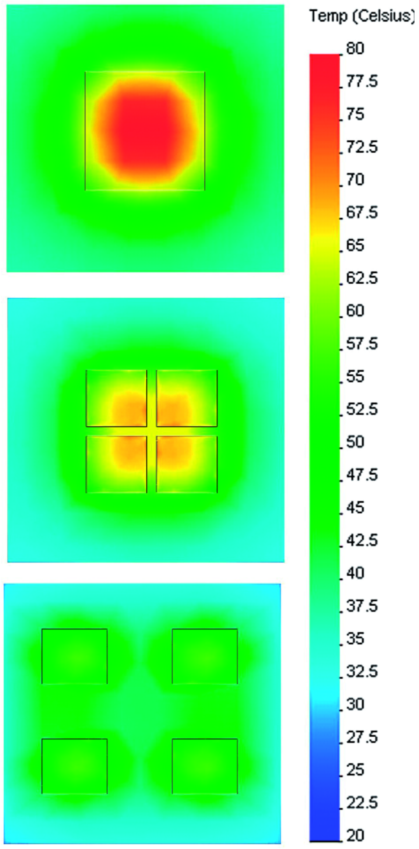

Figure 5: Influence of thermal spreading on chip temperature for same chip area and power dissipation

The R_{th} is a function of the chip size, but also of the distance between the chips (see Figure 5). Oversized chips have a large temperature gradient across the area and poor thermal spreading inside the module. Several small chips with the same overall area but with a little distance between them have a lower R_{th}. If the clearance between chips is small, the chips heat one another up; likewise, the larger the chip clearance, the lower the thermal resistance. The SKiM family achieves the optimum compromise with regards to maximum active chip area and maximum thermal performance: a chip area of between 60 and 80mm² and a distance between chips of 3mm.

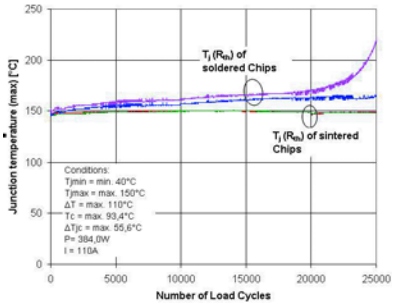

Figure 6: Comparison between soldered and sintered chips in thermal cycling test

The pressure contact on both sides of the chips prevents DCB bending. This can help reduce the poorly conducting thermal paste layer to a thickness of 20…30µm; modules with a baseplate normally have a thermal paste layer of 80…100µm. The ultra thin sintered silver layer, with good heat conducting properties, further reduces the Rth in comparison to the conventional solder layer.

Conventional power module solutions featuring modules with a copper baseplate are not suitable for the extreme thermal cycling that occurs in automotive applications. The different coefficients of thermal expansion put a strain on the joints between the materials. AlSiC baseplates (aluminium silicon carbide alloy) are a reliable alternative but relatively expensive. A pressure contact module with no baseplate is the alternative. Unlike in classic module designs, the low thermal resistance and homogenous thermal spreading on the heat sink in these modules result in lower temperature differences, even in the case of active load cycling. This also increases the module service life.

To improve load cycling capability, even for very high junction temperatures, the SKiM family uses low-temperature sinter technology to connect the chips to the DCB. A solder connection ages as a result of load cycling, resulting in increased thermal resistance and ultimately failure. The sinter connection is achieved using a thin silver layer with excellent thermal conductivity. The melting point of silver is 900°C, which is significantly higher than the maximum chip temperature of 175°C. In the life performance tests no fatigue in the joints was observed (see Figure 6). The elimination of this failure mechanism boosts overall system reliability.

Owing to the use of pressure and spring contact technology for the connections and the removal of the baseplate with solder chip connections, SKiM modules are 100% solder-free power modules. Furthermore, these modules have been optimised to achieve optimum chip utilization and high output currents. In combination with the maximum chip temperature of 175°C, this allows for compact inverter designs with as yet unmatched power density and thermal cycling capacity.

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