juergen.schuderer@ch.abb.com

High-Power Module Platform for Automotive Traction Applications

A paper on a novel power semiconductor module platform for the automotive powertrain was awarded as the best PCIM 2019 paper. Here mold modules are designed for symmetric and minimized parasitics by applying alternating and multilayer current routing. All interconnects are solder-free to provide superior reliability, and to meet present and future automotive requirements, e.g., passing 1000 temperature shock cycles in the range of -40 to 150°C. SiC or Si devices are packaged in the same external outline offering scalability for inverter classes in the 150 – 350 kW power range. A screw-less and O-ring-less 3-phase inverter module is achieved by a laser welding of the mold modules to a low-cost Al cooler enclosure. **Jürgen Schuderer, ABB Corporate Research, Switzerland; and Andreas Apelsmeier, AUDI AG, Germany**

The recent electric vehicle (EV) outlook from the International Energy Agency projects a rapid growth of global vehicle stock from 3 million vehicles in 2017 up to 228 million electric vehicles by 2030. This tremendous growth will come along with the need for cost-effective and reliable power electronics inverters within the electric powertrain of hybrid, plug-in hybrid, and battery-electric passenger vehicles, as well as light-commercial vehicles, buses, and trucks. At the heart of the inverter are power semiconductor devices arranged in multi-chip power modules that control the motor torque and speed via pulse width modulation (PWM).

Power modules must be optimized for mechanical integration into highly compact inverters that are mounted in space-restricted engine compartments of Evs. Strategies for power module footprint reduction are the expansion of current routing into the third dimension, the improvement of the cooling path to reduce chip area, and the high-temperature operation of wide-bandgap (WBG) semiconductors to extract more power from the same outline. This goes along with the trend to integrate the power inverter with the electric motor into a single unit to eliminate interfaces and make use of common infrastructure (structural, cooling, busbars).

Thus it is expected that the automotive market dominance will significantly drive innovation and lead to accelerated implementation of new materials and manufacturing methods, which need to be carefully assessed with respect to reliability issues. Examples are the deployment of fast-switching WBG devices, application of new bonding technologies like planar topside bonding, sintering, PCB embedding, and the heterogenous integration of passives, diagnostics sensors, drivers, transceivers, and other on-board components. Finally, commercial vehicles like buses and trucks are designed for longer lifetime than passenger EVs, e.g., 60,000 vs. 7,000 hours, and the resulting increased reliability demands need to be considered.

Power module design concept

A SiC / Si power module platform was developed to address automotive performance requirements (Figure 1) .

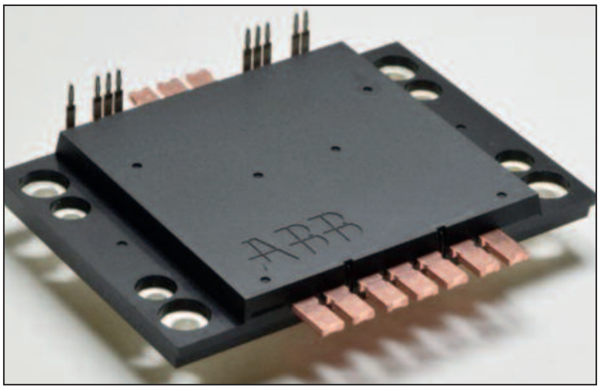

Figure 1: 900 V SiC mold module, Gen 1 design

To address the cost issue, a mold module approach has been selected that does not require any housing. The mold encapsulation provides 1) good environmental protection by low moisture absorption and water vapor diffusion, 2) good cycle reliability by its hard-mold, compressive and low-coefficient of thermal expansion (CTE) encapsulation, and 3) excellent protection against shock, vibration and handling damage.

A completely solder-free power module is realized for the highest cycle reliability and robustness standards. All interconnections are either sintered or welded. Furthermore, this approach allows for a superior manufacturing throughput, because the sintering of all power module components can be realized in a single process step.

To allow for SiC fast switching, power loop and gate loop inductances as well as coupling coefficients are rigorously minimized. This is achieved by applying a systematic alternating (+/-/+) signal routing of power- and gate circuitry to substrate and terminals, and by using multilayer signal distribution inside the module.

A low-cost cooler enclosure is realized by laser welding of mold modules into a structure based on cheap embossed Al sheets. In this manner, a compact 3-phase inverter module is achieved without the need for screwing or clamping of O-ring sealings that could pose a risk of leakage.

The proposed power module offers several aspects of scaling. First, two different substrates are applied to assemble either a high-power SiC, or a lower-power Si version for the identical external outline. Second, due to a special symmetric substrate layout, further power scaling is possible by adding or removing chips along the length of the module (x-direction in Figure 2) without impacting stray inductances and coupling coefficients. Finally, module cost can be scaled by applying different power module component materials (substrates, baseplates, bond materials) to optimize for the right cost-performance ratio for the specific target vehicle.

Half-bridge module design

The mold modules are designed in half-bridge configuration. Two different types were developed, a 900 V SiC version for screw attachment to the cooler, referred as Generation 1 (Gen 1), and a 1200 V SiC and Si version for direct cooler bonding, referred as Generation 2 (Gen 2), see Figure 2. Both types were designed using similar packaging technologies and materials.

A CTE-matched pin-fin baseplate made from AlSiC with a pin-field optimized for maximum heat transfer and small temperature differences between parallel chips is applied to support a homogeneous current sharing. A main ceramic substrate made from Si_3N_4 is bonded to the baseplate by Ag-sintering. Semiconductor dies, NTC temperature sensor and external per-chip gate resistors (only SiC version) are Ag-sintered to the main substrate. Top plates made from Cu are Ag-sintered to the power semiconductor chip top surface to enable high-reliability Cu source wire bonds. Al is used for the remaining bond wires (gate, auxiliary source, substrate-to-substrate bonds), see Figure 3. Al_2O_3 second-level substrates are Ag-sintered to the main substrate and used for low-inductance current routing of the control signals. Cu power terminals and auxiliary terminals with press-fit pins are bonded to the main substrate by ultrasonic welding, see Figure 4.

The module is encapsulated by an epoxy-based transfer mold material with optimized CTE. A screw thread is embedded in the mold compound that allows tight fixation of the gate driver board and alignment of the modules during assembly on the cooler enclosure. The substrate and terminal design is optimized to achieve symmetric and minimized stray inductances and cross-coupling. This is achieved by the following design approaches, see Figure 5.

The DC commutation loop and the gate loops of the half-bridge module are arranged in an alternating design so that the magnetic fields cancel out to a large extent. In addition, a control signal distribution on second level substrates reduces the cross-coupling from the power into the control loop.

Beside the small commutation loop inductances, it is a desired feature of the given designs that gate inductances and mutual inductances are small and symmetric across parallel chips allowing for fast and balanced switching. A simulation of the per-chip switching transients for the SiC Gen 2 module is shown in Figure 6. Note that the data indicates a small difference of chips 1 - 4 vs. 5 - 8. This comes from the die arrangement in two rows leading to slightly different coupling and gate inductances.

Packaging technologies

SiC and Si chips were sintered on Si_3N_4 ceramic substrates with Ag or NiAu surface plating (nano-particle based Ag materials sintered at pressures ranging from 10 to 20 Mpa and temperatures around 250°C). A pick & place tacking process was used for accurate alignment, and chips and top plates were sintered in a single step. Thermal shock cycling tests between -40°C

Figure 2: 1200 V SiC and Si mold module, Gen 2 design

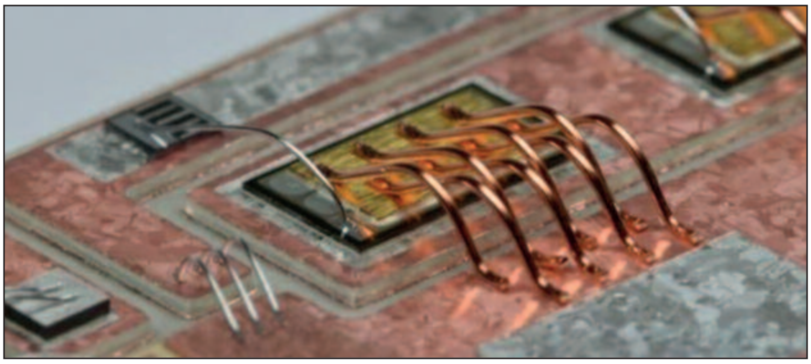

Figure 3: Cu source wire bonding on top plate; Al wire bonding for gate, auxiliary source (not shown), NTC (bottom left) and interconnects on substrate

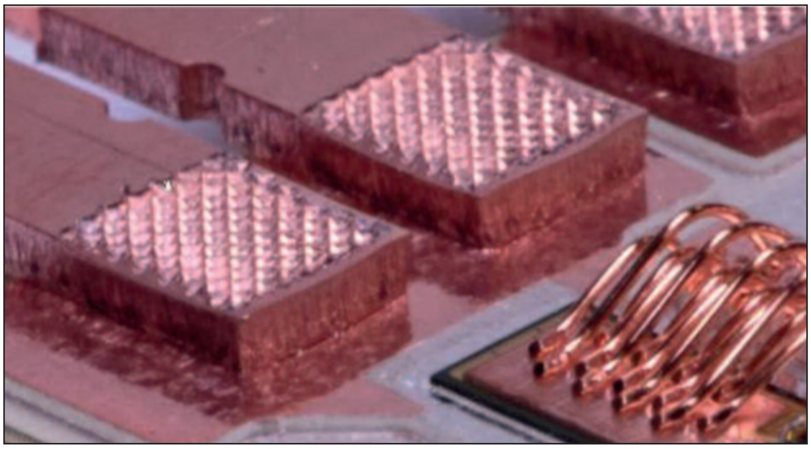

Figure 4: Ultrasonic welded leadframe terminals

juergen.schuderer@ch.abb.com

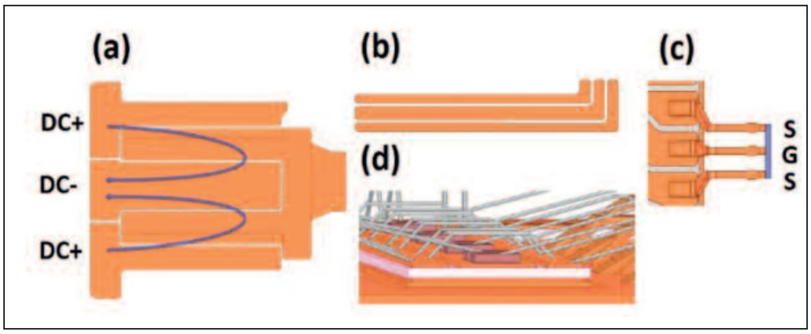

Figure 5: Alternating current routing for DC+ / DC- current path (a); (b) and (c) Kelvin source and alternating control signal routing on substrate and terminals; (d) Multilayer signals on second level substrate for minimal magnetic coupling into the gate - source control loop

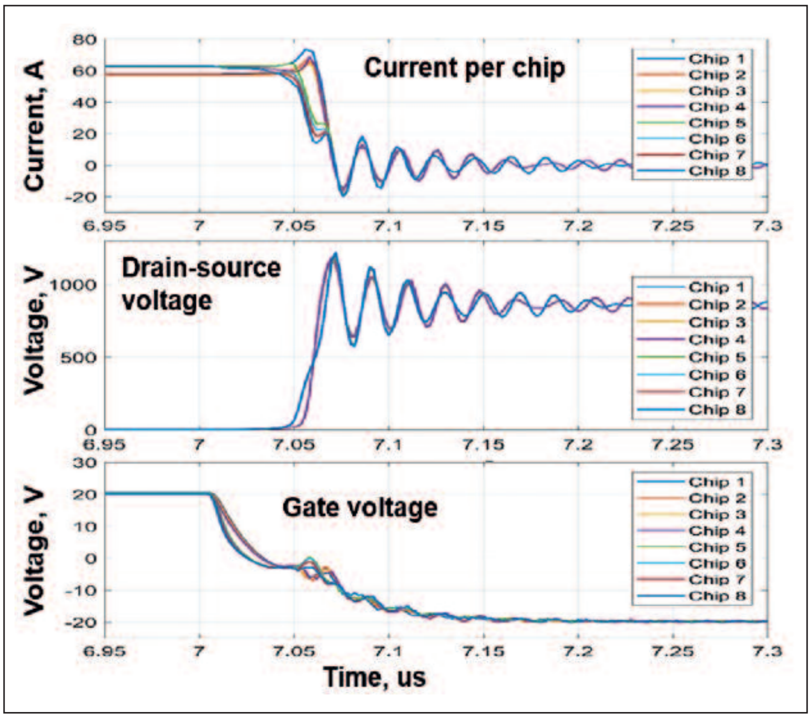

Figure 6: Simulated switching waveforms for turn-off event based on parasitics extracted at 100 MHz; high-side chips of Gen 2 SiC module are plotted

to 150°C with a dwell time of 5 minutes at each temperature were conducted to verify the sinter bond quality. After regular intervals of cycles, the samples were inspected using scanning acoustic microscopy (SAM) to detect any delamination or degradation of the bond layers.

It is well known that apart from the die attach, the chip topside interconnection is a main limiting factor for the lifetime of power semiconductor devices in active load cycling conditions. To improve this issue, sintering a top plate on devices with standard Al metallization and NiAu plating was performed. The top plate acts as a buffer and allows for Cu wire source bonding with superior power cycling lifetime. Different materials (Cu, Mo) and thicknesses (50 µm, 70 µm, 100 µm, 150 µm, 200 µm) have been tested. As a conclusion, a top plate made of Cu or Mo in the thickness range of 50 – 100 µm showed the best reliability in thermal shock cycling.

Heavy Cu wire bonding has been proven to be a superior alternative to Al wire bonding with greatly improved power cycling lifetimes (due to the higher electrical and thermal conductivities and greater mechanical strength of Cu). However, the process comes with some challenges such as high bond forces, narrow process window, influence of top plate material, thickness and surface properties, as well as accelerated tool wear. Thus a 300 µm Cu wire bonding process was optimized by pull and shear testing. A special focus was dedicated to identify the best compromise for the bond force to avoid cratering and chip topside damaging (gate-source short), and to achieve sufficiently high shear forces. As a result: whereas Al wire bond reference modules failed at around 20,000 cycles, the sintered top plate and Cu wire bonded modules were able to reach more than 1,000,000 cycles without failure.

Among the different ceramic substrate materials commonly used for high-power semiconductor modules, Al/AlN DBA and Cu/Si3N4 AMB substrates have been reported to achieve the highest thermal cycling capabilities. Since Al metallization can be problematic for the ultrasonic welding of Cu terminals, a Si3N4 AMB substrate was selected. In addition, to achieve highest-level reliability when targeting high-temperature operation of SiC, a substrate sintering process has been developed.

Different baseplate materials (Al, Cu, AlSiC), different bond line thicknesses (20 and 40 µm) and different sinter materials (Ag film, Ag preform with metal core) were tested by thermal shock cycling. It turned out that the metal-core sinter preform and an AlSiC baseplate provide best reliability performance. Virtually no delamination of the substrate-to-baseplate attach was found after 1,000 thermal shock cycles both from −40°C to 150°C and from −5°C to 200°C, as well as high-temperature storage tests for 1,000 hours at 200°C and 225°C.

Three-phase inverter module and cooler design

Water-glycol cooling of power semiconductor modules by means of pin fins has become a preferred way in the thermal management of traction inverters of EVs. Pin fins are either integrated in the module's baseplate for direct cooling, or are part of a separate, closed cooler, to which the modules are attached. Whereas the Gen 1 module was designed for screw attach and sealing by an O-ring, the Gen 2 module has the full cooler metallurgically bonded to the mold modules.

The cooler assembly concept and final inverter module with cooler are shown in Figure 7. The cooler consists of three basic parts: an Al frame plate that is laser-welded to the mold modules in a first step, an Al cover plate that is welded to the frame in a second step, and fluid ports that are welded to the cover in a final step.

A critical bonding process is the welding of the cooler frame to the mold module baseplates. Heat input during this welding step must be minimized to avoid thermal damaging of the modules. Due to this reason, laser welding has been chosen since it is an exceptionally fast process, limiting the temperature rise at the mold compound side of the power module to less than 200°C. Careful process optimization and well-designed jigs are required to achieve a fluid-tight joint with high process repeatability. As an example, material cracks within the welded bond lines may occur that can lead to coolant leakage.

Switching losses and rating

Double-pulse testing was conducted to determine the switching losses and to assess the power rating to the different module variants. Tests were performed in the temperature range from −20 to 150°C at DC-link voltages up to 850 V, and for currents up to 600 A. Switching waveforms for a Gen 2 SiC hard switching are shown in Figure 8.

The measurement was done at a DC-link voltage of 650 V, a current of 400 A, a temperature of 150°C, zero gate resistance (hard switching) and for a stray inductance of the test setup of about 30 nH. Pronounced oscillations results from the fast switching combined with the high stray inductance of the tester. It is therefore important to operate the module in a low inductive inverter environment for optimal performance. In general, however, the traces are quite clean. This is especially important for the critical gate voltage trace (to avoid parasitic turn-on and other issues).

Switching losses as measured by double-pulse testing are reported in Table 1. SiC losses are given for a gate resistance of 1.7 Ω, and for a hard-switched configuration with 0 Ω. In addition, Gen 2 Si losses and Gen 1 SiC losses (at a DC-link of 400 V) are given. Note that tests were performed with different double-pulse setups and gate drivers which makes a direct comparison difficult.

Conclusions

An automotive SiC and Si power module platform targeting inverter classes of premium and commercial EVs in the power range of 150 – 350 kW was presented. Mold modules are bonded to an integrated cooler enclosure that allows for a compact, and screw-less inverter design. High-reliability packaging technologies are employed enabling operation up to 200°C junction temperature.

Literature

"High-Power SiC and Si Module Platform for Automotive Traction Inverter", Jürgen Schuderer, BPA Winner, ABB Corporate Research, Switzerland, and Andreas Apelsmeier, AUDI AG, Germany, PCIM Europe 2019 Proceedings

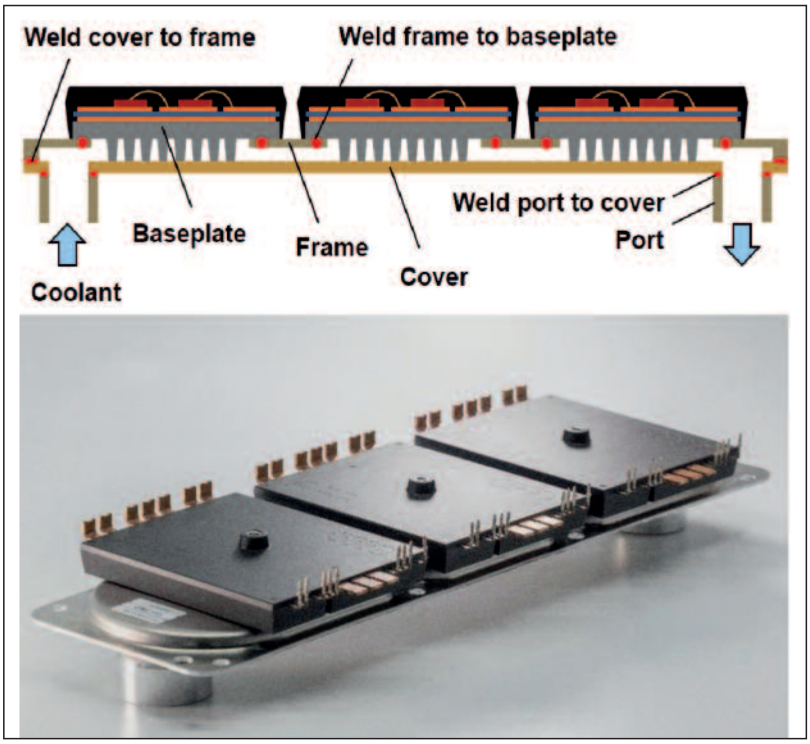

Figure 7: Cooler schematics and 3-phase power module

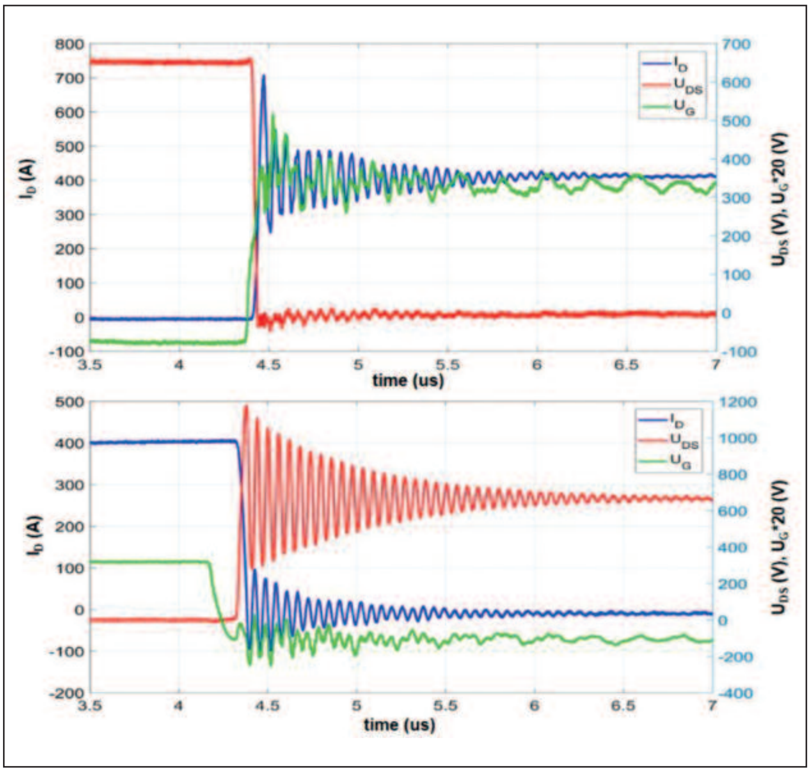

Figure 8: Turn-on (top) and turn-off (bottom) switching waveforms of SiC Gen 2 module at 25°C; blue: current, red: voltage, green: gate voltage

Module type	R_G [Ω]	E_{on} [mJ]	E_{off} [mJ]	E_{rr} [mJ]
SiC Gen 2	1.7	17.8	6.9	-
SiC Gen 2	0.0	1.4	10.8	-
Si Gen 2	0.0	23.9	71.1	50.1
SiC Gen 1	1.3	3.7	4.1	-

LEFT **Table 1:** Switching losses measured by double-pulse testing; Gen 2: U = 800 V, I = 400 A, Gen 1: U = 400 V, I = 400 A; T = 100 - 150 °C; RG = total chip-external gate resistance