# Power Electronics Packaging Revolution Without Bond Wires, Solder and Thermal Paste

Power module packaging is driven by the ever increasing demand for higher power densities, reliability improvements and further cost reductions. The known reliability limitations of traditional solder joints and bond wires are holding back significant power density increases made possible thanks to higher junction temperatures and the future utilization of wide bandgap devices. Today, silver sintering has already started to replace the solder joint between chip and DBC substrate, leaving one major reliability bottleneck: the bond wire interface on the chip surface. **Peter Beckedahl, Manager Application and Concepts, Semikron, Nuremberg, Germany**

For some years now, the elimination of bond wires in power modules has been under discussion in industry and academia. Most of the new packaging approaches have been based on soldered or welded bumps, as well as on embedded interconnection technologies. The innovative packaging technology, named SKiN Technology, presented here takes the silver (Ag) sinter joint and applies it to all remaining interconnections in a modern power module. In addition to the double-sided sintering of power chips, the entire DBC is sintered to the heat sink. The resulting device has a very high power density and demonstrates remarkable thermal, electrical, and reliability performance compared to traditional packaging technologies.

## Sinter technology

Silver sintering is an established technology which has started to replace the soldering of chips to DBC substrates in mass production. Thanks to its unprecedented reliability and thermal behavior, it makes power modules better suited to higher temperatures and demanding applications such as electric vehicles and wind turbines. However, two issues remain unaddressed: how to replace wire bonding on the chip top side, and how to connect the power module to the heat sink.

SKiN Technology resolves both these matters by using Ag sinter technology for all interfaces. The chip surfaces are sintered on the top side to a flex layer and the chip bottom to a DBC substrate, which in turn is sintered to a heat sink or base plate. Figure 1 shows a schematic drawing of this packaging technology. The special flex foil has a metal base power layer which is comparable to bond wire diameter in thickness and serves to connect the chip top surface. A thin metal layer on top represents the gate and sensor tracks which are connected to the power layer by vias. The two metal layers are insulated from each other by polyamide. The top layer can also be used for SMD components such as temperature sensors and gate resistors. The second sinter joint connects the back of the chip to a standard DBC substrate. All standard IGBT and diode chips can be used for this process, they need just an additional noble metal contact treatment on the chip top side.

The third joint connects the back of the DBC using large-area Ag sintering to an Aluminum (Al) pin fin water-cooled heat sink. The power terminals are sintered to the DBC in the same process step, resulting in a power module in which all interconnections are made with Ag sinter joints. The main advantages of the new SKiN Technology and its performance improvements are as follows:

- Power Density: The use of an Ag sinter layer instead of thermal paste will increase the power density as a result of the reduced thermal resistance chip to coolant. The large-area metal connection on the chip top surface will further improve the heat spread of the die.

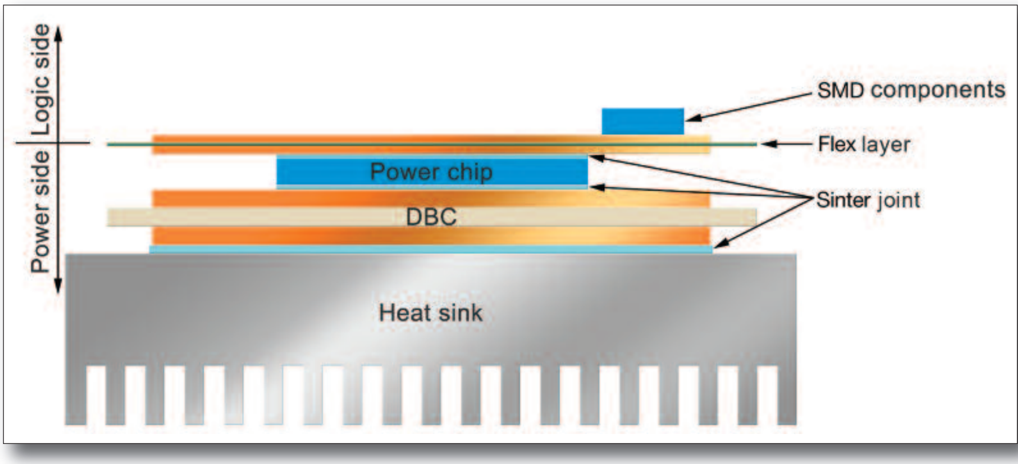


**Figure 1: A schematic drawing of SKiN device**

- Reliability: The replacement of Al bond wires by sintered flex foil will increase the power cycling capability thanks to better CTE (coefficient of thermal expansion) compatibility of the materials used, and the large-area connection between chip surface and contact medium.
- Electrical Properties: The use of the sintered flex foil instead of the Al bond wires will increase the maximum surge current rating of the dies as a result of the increased cross-section and area of the chip surface contact. In addition the module stray inductance is decreased due to a reduced loop geometry and wide traces.

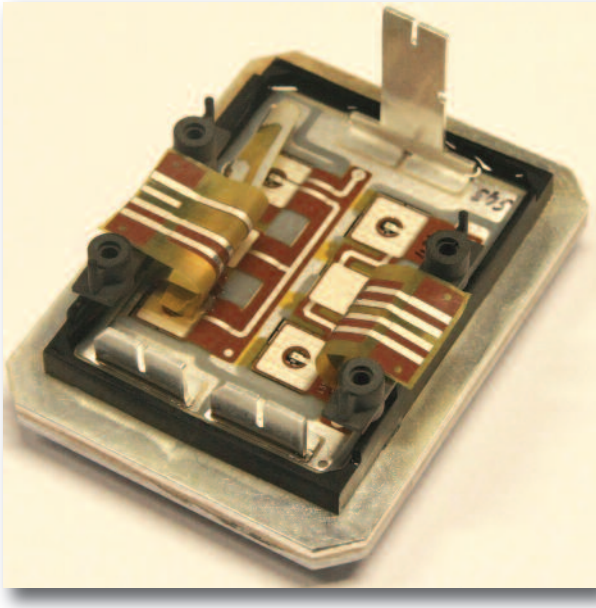

**Figure 2: SKiN half-bridge 600V/400A module**

## Power module design

The prototype design used for this performance comparison is a 600V, 400A half-bridge power module with an aluminum pin fin heat sink.

The chipset of the prototype samples consist of 2 x 200A, 600V IGBT and 1 x 275A, 600V CAL freewheeling diode per switch. The power terminals are placed on the opposing short sides of the heat sink. The auxiliary contacts from the IGBT to the gate driver are provided by the flex layer itself, which is extended across the long side of the DBC (see Figure 2).

In order to benchmark the new packaging concept not only with traditional power module designs, identical devices have been built with standard Al bond wires for the die surface contact. To obtain maximum performance, each chip is contacted with 12 bond wires (see Figure 3). The surface of the diode is contacted with three stitches per wire; the IGBT with four stitches.

A significant difference between the flex layer and bond wire design is the contact area of the chip surface. While the bond wires are in contact with around 21 percent of the total metallized chip area only, the flex design exhibits a contact area of 50-85 percent, depending on the chip type.

## Thermal resistance

The maximum power dissipation of the semiconductors is limited by the maximum junction temperature ($T_j$), the coolant temperature ($T_a$), and the thermal resistance (Rth) from chip to cooling medium according to the following equation:

$$P_v = \frac{(T_j - T_a)}{R_{th(j-a)}}$$

Especially in automotive applications where coolant temperatures above 85°C are needed, the temperature difference to the maximum allowed junction temperature becomes small which leads to reduced power densities and the need to reduce the thermal resistance to a minimum.

The new power module meets these requirements with a fitting solution: a high-density pin fin Al heat sink and an Ag sinter joint between the DBC substrate and the heat sink. No thermal paste is used, which has a significant contribution in the thermal performance of standard packages.

The measurements were performed using a three-phase automotive inverter setup (Figure 4) with a 50 percent glycol mixture and 70°C coolant temperature. The water inlet and outlet is on the left-hand side; distribution through the three modules is obtained using three parallel flow channels.

For the test all IGBTs are electrical

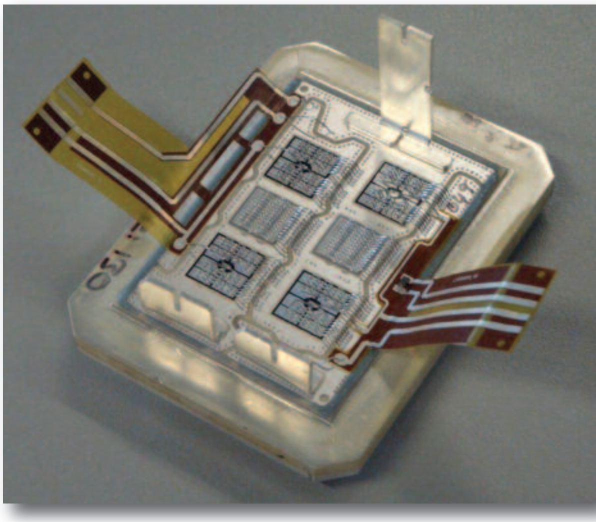

**Figure 3: Benchmark module with bond wires**

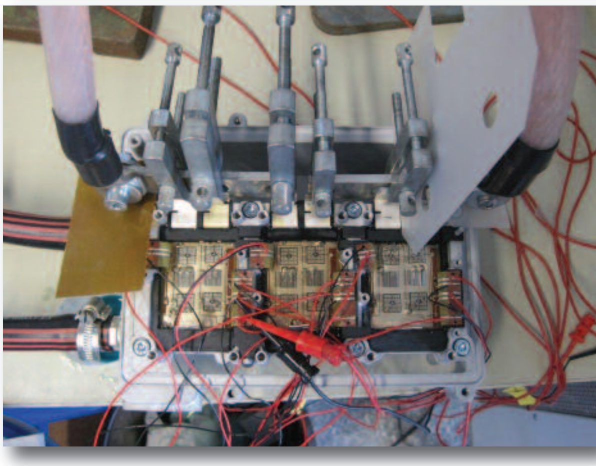

**Figure 4: Inverter setup used to measure thermal resistance**

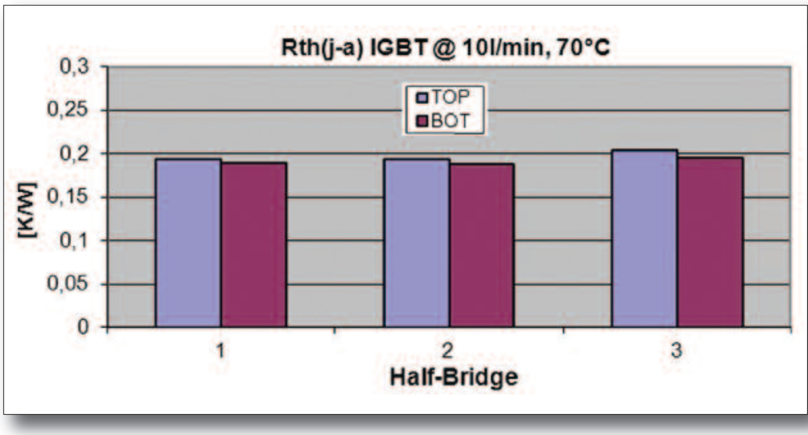


**Figure 5:** $R_{th(j-a)}$ **of the six IGBT switches**

connected in series and heated by an adjustable DC current. In this way it is possible to measure the power losses as well as the junction temperatures most accurately since it is not disturbed by switching transients.

The difference in thermal resistance (junction to water $R_{th(j-a)}$) between the upper (TOP) and lower (BOT) IGBTs, as well as the variation between the half-bridges is less than 10 percent and is shown in Figure 5. The lower switch of a half-bridge has a slightly better thermal resistance than the upper switch. This is due to the larger DBC copper area beneath these chips which leads to better thermal spread. This effect is well known in power module designs due to layout restrictions.

A summary of the thermal results is given in Table 1.The total thermal resistance $R_{th(j-a)}$ is exceptionally good, while the pressure drop remains at a very low level. A figure of merit is given in the second column were the thermal resistance is multiplied by the total chip area. This figure can be used for an easy comparison to competing solutions.

At a coolant temperature of 70°C, a flow rate of 10l/min and a maximum junction temperature of 150°C, it is possible to draw 205W/cm² chip area out of the system. Traditional high-power inverters with thermal paste between the power module and the water cooler reach just 100-150 W/cm² chip area. Please note that the flow rate in Table 1 is given for three half-bridges with parallel water paths. The flow per half-bridge is only one third of the total flow rate. Of course it is also possible to arrange the design with a serial coolant flow through the three phases which will lead to an even higher power density.

The question remains as to how a traditional module would perform if it were mounted on the same high-density Al pin fin cooler used for the SKiN module. To investigate this, thermal simulations were performed where the Ag sinter joint between DBC and heat sink was replaced by a thermal paste layer of only 20μm. Such a thin thermal paste layer is only possible using sophisticated pressure contact modules without baseplate, like the SKiiP or SKiM power module family. Modules with baseplate would require a much thicker thermal past of 80-150μm. The simulation results confirmed the large impact that the thermal paste layer has. Even for a layer of just 20μm, the total thermal resistance will increase by 23-30%, depending on the coolant flow rate.

| SKiN Module | | Benchmark Module | |
|---|---|---|---|
| Sample | A | Sample | A |
| Top | 2666 | Top | 2092 |
| Bot | 2690 | Bot | 2108 |
| Top | 2691 | Top | 2105 |
| Bot | 2662 | Bot | 2096 |
| Top | 2696 | | |
| Bot | 2662 | | |
| Top | 2691 | | |
| Bot | 2656 | | |
| min | 2656 | min | 2092 |
| max | 2696 | max | 2108 |
| mean | 2677 | mean | 2100 |
| | 127% | | 100% |

**Table 2:** **Diode surge forward current ($I_{FSM}$) comparison**

## Surge forward current

The diode surge forward current ($I_{FSM}$) was measured using a standard half sine wave current surge of 10ms duration at 25°C. The results for maximum peak current level before destruction are displayed in Table 2.

The surge current rating of the flex layer module is 27 percent higher than the bond wire module. Due to the larger cross-section and shorter track length in the flex layer design, the surface contact fuses later than the bond wire module.

This behavior is particularly important for active front-end or generator applications, since it compensates for the reduced chip area which has been

| SKiN Module IGBT | | | |
|---|---|---|---|
| Flow | $R_{th(j-a)}$ | $R_{th(j-a)}$*A | Pressure Drop |
| | K/W | Kmm²/W | mbar |
| 5l/min | 0,225 | 45 | 30 |
| 10l/min | 0,194 | 39 | 90 |
| 15l/min | 0,182 | 36 | 185 |

**Table 1:** **Summary thermal resistance**

made possible from the improved thermal behavior of the integrated pin fin cooler.

## Power cycling

Power cycling is the main qualification test to validate the lifetime required by the application mission profile owing to cycling loads. The most demanding applications are electric and hybrid vehicles, elevators, as well as wind turbines. The failure modes for power cycles are a combination of the typical bond wire lift-off and solder joint degradation in the layers below the chips. What cause of failure dominates depends on numerous factors such as cycle time and chip size. The replacement of the solder with a sinter layer has already eliminated one failure mode, leaving only the bond wire as the remaining reliability weak point. Single-sided sintered power modules have already in the past demonstrated a 2-3 fold improvement in power cycling.

Power cycling tests were performed on both module types under identical conditions with $\Delta T_j$ = 110K (40°C to 150°C) and a complete cycle times of 14 seconds. The control strategy for the power cycling test was a fixed time adjustment, which is the harshest and most realistic test mode since it does not compensate for any type of degradation during the test.

Figure 6 shows the preliminary test results. The power cycling results for the benchmark modules are well within the expected curve (blue line) for single-sided sintered modules in the range of 60k cycles. The results for the SKiN power module by far exceed the target curve (red line), which is already 20 times higher than the industrial standard (green line). The modules passed more than 700k cycles until failure. In addition, short power cycles with a $\Delta T_j$ of 70K (80°C to 150°C) were started. Here the modules have already passed 3 million cycles. Tests will be continued to EOL (end of life).

The preliminary results demonstrate the unprecedented reliability of the new double-sided sintered power module. The target was exceeded, resulting in a 70-fold improvement in performance over the industrial standard and a ten-fold



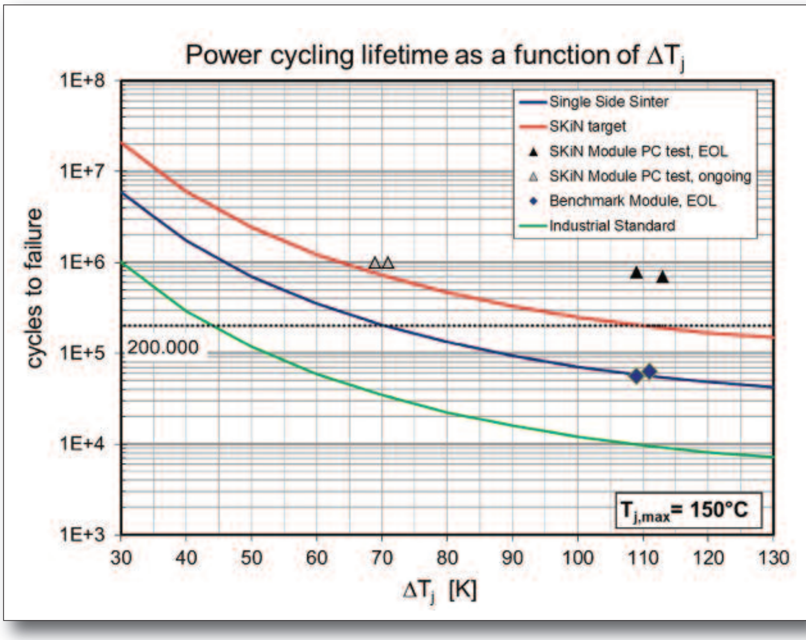


**Figure 6: Preliminary power cycling results**

improvement over the single sided sintered benchmark module.

It is important to mention that these results are from standard 600V IGBTs with a chip thickness of only 70μm and a standard Aluminum top side metallization. Only an additional thin noble metal surface finish is required. The SKiN packaging technology does not require any major changes in chip metallization materials or layer thickness.

## Conclusion

SKiN Technology is a new packaging technology without bond wires, solder layers and thermal paste. All interconnections to chip top and bottom surface, DBC to heat sink and power terminals are made using Ag sinter joints. The bond wires have been replaced by a special flex foil which increases the chip surface contact area by a factor of 4.

In order to demonstrate the exceptional performance improvements of the overall system and in particular the flex foil, a comparison with a benchmark module featuring conventional Al bond wires was performed. Thanks to the elimination of thermal interface materials and the integration of a high-performance pin fin heat sink, it is possible to double the power dissipation in comparison to conventional designs. The elimination of the thermal paste layer alone leads up to a 30 percent improvement in the total thermal resistance junction to water. Owing to the modified geometry and increased chip contact area, a 27 percent increase in diode surge forward current capability has been achieved.

The power cycling performance demonstrates an unprecedented 70-fold improvement over the industrial standard and a 10-fold improvement over the single-sided sintered benchmark module. Further activities are underway in order to exploit the new possibilities of the dual-layer flex foil. These are, in particular, a further improvement in thermal resistance resulting from double-sided cooling and the integration of passive and active components for gate drive, current and temperature sensing.

## Literature

*T. Stockmeier, P. Beckedahl, C. Göbl, T. Malzer: SKiN: Double side sintering technology for new packages, ISPSD 2011.*

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