Adhesive Bonding to Replace Soldering of Power Modules

Epoxy-based adhesives can generally produce high-strength and stable connections. Whether this also applies to the high requirements in power circuits was the subject of a current research project.

Arno Maurer

Adhesives that can do more than just adhere can be summarized as functional adhesives. Depending on the requirements of the application, they provide additional properties which, for example, enable or inhibit the transmission of heat, light, electrical current or mechanical forces.
Electrically conductive adhesives are widely used in microelectronics for the assembly and contacting of semiconductor chips, but increasingly also for the connection of sensors, actuators, motors or heating elements. Furthermore, in photovoltaics, they offer the possibility of electrically contacting solar cells in modules /1/.
In contrast, thermally conductive adhesives are used to connect components to heat sinks or heat-dissipating substrates in microelectronic circuits /2/. New applications, such as the heat management of power semiconductors or traction batteries, require higher thermal conductivities than previously, as well as application-specific processing properties and performance. This was the reason for the development of a new generation of heat-conducting adhesives with optimized thermal and mechanical parameters which, in cooperation with the customer, are tailor-made for the respective application /3/. To ensure high structural strength with simultaneous thermal and chemical resistance, these adhesives are preferably formulated on the basis of epoxy systems. The resulting joints are able to convey mechanical forces over the whole bondline while being thermally and electrically conducting at the same time. Thus, in many cases, they offer an interesting alternative to soldering, welding or mechanical bonding. In contrast to the conventional methods, adhesive bonding is also possible with difficult material combinations and avoids unwanted effects, such as deformations or discoloration.

Adhesive joining of power semiconductors

Power semiconductors are devices suitable for the switching of currents of above one ampere and voltages of above approx. 24 volts. With this property, power semiconductor circuits are found in industrial control technology and railway technology, for example, but increasingly also in vehicle technology. Particularly in electric and hybrid vehicles, high currents and voltages have to be converted and controlled. The power semiconductor industry is experiencing strong growth overall /4/.
Suitable electronic packaging techniques for power semiconductors /5/ *(Table 1)* are also subject to a dynamic development. Classical soldering methods can be replaced in part by silver sintering or liquid phase sintering, not least of all driven on by the EU RoHS directive, which

Connection techniques	Material	Bonding temperature	Melting point* or decomposition**
Lead-free soldering	Ag-Sn solder	215 - 230 °C	215 - 230 °C*
Electrically conductive bonding	Silver-filled epoxy	120 - 180 °C	220 - 250 °C**
Silver-sintering	Silver paste	240 °C	961 °C*
Liquid phase sintering (TLP)	Multilayer film Sn-Ag-Sn (IMTEK)	210 - 235 °C	650 °C*

Table 1 > Comparison of connection techniques for power semiconductors.

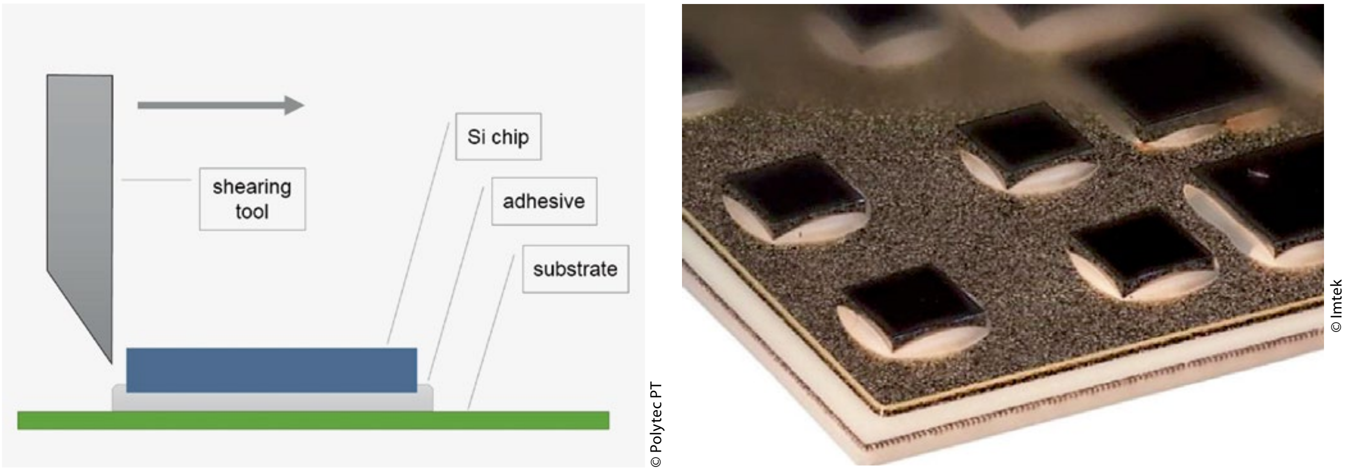

Figure 1 > Schematic structure of the die-shear test (left) and glued test pattern (right).

Industrial Joint Research Project:
Process for Conductive Bonding of Components for Power Electronics

The aim of this publicly funded IGF project (IGF-No.: 00.491.ZBG/DVS-No.10.073) was to illustrate a process for the conductive bonding of active and passive components on substrates of power electronics. The object was not the development of a fundamentally new production process, but rather the verification of the suitability of conductive bonding using adhesives from different manufacturers. The approach is mainly based on material characterization and optimization, the production technology of the test specimens for component-related thermal-electrical properties and reliability tests, as well as the production of functional patterns for an application-oriented laboratory setup. The project was funded as part of the Program for the Promotion of Industrial Joint Research (IGF) during the period from July 1, 2013 to December 31, 2015. The processing centers were the Laboratory for Assembly and Packaging Technology at the Albert-Ludwigs-University Freiburg, Department of Microsystems Engineering (IMTEK) as well as the Chair of Power Electronics at Otto-von-Guericke University Magdeburg, Institute of Electrical Energy Systems (IESY). The final report on the project is available on the Freiburg document server at https://www.freidok.uni-freiburg.de

prescribes new lead-free interconnecting technologies. Lead-free soldering requires higher process temperatures than previously, with corresponding stresses on the materials involved. Electrically conductive bonding has been applied increasingly in microelectronics for many years and is also available for higher performance classes, promoted by new developments in adhesives and substrate materials.
As is known, an advantage of bonding are quite low process temperatures combined with a low degree of process complexity. This was the reason for the implementation of the funded research project "Process for conductive bonding of components for power electronics" (see info box), which was jointly edited by the IMTEK Department of Microsystems Engineering at the University of Freiburg and by the IESY Institute for Electrical Energy Systems at the University of Magdeburg/6/. The results of the research project demonstrate the high potential of conductive bonding as an alternative to soldering as a joining technique /7/. In the following, some findings concerning the mechanical, electrical and thermal properties of a selection of the adhesives used and the consequent suitability for the bonding of power semiconductors are presented.

Mechanical properties and operational strength

Besides the process capability, the achievable joint strength and the resistance to thermal and mechanical stress during the product life is critical for the success of a joining process. Epoxy-based adhesives can generally produce high-strength and stable connections. The aim of the project was to clarify whether this also applies to the high requirements placed on power semiconductor assemblies.
For this purpose, die-shear test specimens were first prepared using various conductive adhesives *(Figure 1)*, including Polytec EC 112, a 2-part adhesive for standard applications in microelectronics, as well as EC 242, a new product with a low specific resistance at approximately 5 * 10^{-5} Ohm cm and a high thermal conductivity of 4.2 W/mK /8/.
The test pieces were 2.8 x 2.8 mm silicon chips and the substrate consisted of Al_2O_3-DBC ceramic circuit boards (in part, also FR4 printed circuit boards) with either NiAu or Cu metallization. The test samples were exposed in a temperature shock chamber for up to 2500 temperature cycles of -40 °C to 150 °C (FR4: 125 °C) for one hour each. The resulting shear strengths are presented in *Figure 2*. EC 112 shows a relatively constant shear strength between 20 and 30 MPa over 2500 temperature cycles while the EC 242 on the NiAu surface initially shows the best values at about 45 MPa. The strengths decrease over the course of aging, as do the test patterns adhered to the copper surface, but they still present good values above 25 MPa after 2000 cycles. The EC 242 shows the better strengths overall; it is also temperature-resistant up to 230 °C in continuous oper-

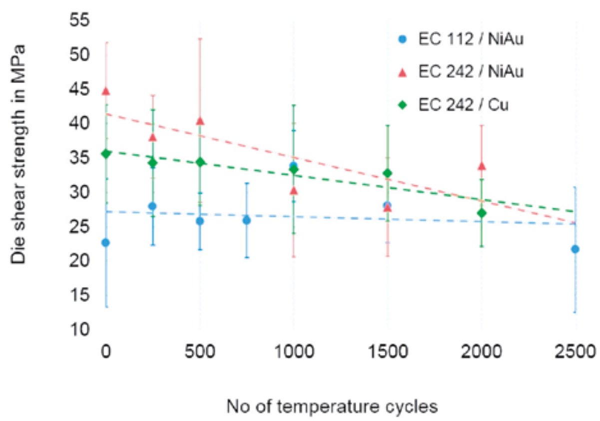

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Figure 2 > Die-shear strength of specimens bonded with conductive adhesives vs. number of temperature shock cycles.

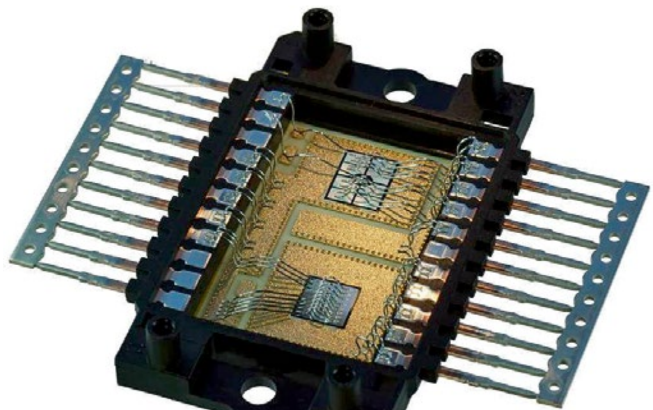

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Figure 3 > Test module with IGBT and diode, photo courtesy of Imtek.

ation and has a glass transition temperature of approximately 110 °C.

With respect to the mechanical properties, the project has also shown that the deformation of the bonded modules generally remains smaller than that of the soldered modules, due to lower mechanical stresses during the bonding process.

Electrical and thermal properties

To determine the performance during operation and to create a life-cycle model, the project partners at IMTEK used the specified adhesives to produce application-oriented power modules, each consisting of an IGBT (chip area 8 x 10 mm) and a diode (8 x 8 mm) *(Figure 3)*; these were tested by the IESY under operating conditions in comparison to AgSn3.5 soldered modules /9/. *Figure 4* shows a detail of the power semiconductor glued with the EC 242 (layer thickness of the adhesive joints is approximately 30 - 50 µm).

A gate-emitter voltage of 15 V was applied to the semiconductor chips for a static electrical characterization, and the I/U characteristic at the collector was recorded at collector currents of up to 150 A. From the linear part of the I/U curve the so-called differential electrical resistance was determined, which is composed of the resistance of the module, of the semiconductor and of the materials and interfaces of the connection. Since only the connecting technology changes when the kind of joining is changed from solder to adhesive, the differential resistance can be used as a comparison variable for the electrical properties. *Figure 5* shows the resistances determined in this manner at 25 °C and 125 °C, respectively. Compared to the solder, the EC 112 has higher resistances, the EC 242 slightly increased ones, and even lower resistances in the case of the diode. As a result, even at elevated operating temperatures, this adhesive is electrically equivalent to the solder.

The thermal resistances (Rth) were measured on a special test bench at 20 °C and under a 50 A load. It can be seen in *Figure 6* that the resistances of the EC 112 differ greatly from those of the solder, while the resistances of the EC 242 is only about 15 to 20 percent higher than the comparison values. However, since the electrical losses increase with increasing operating temperatures and then produce more heat, this deviation is not negligible.

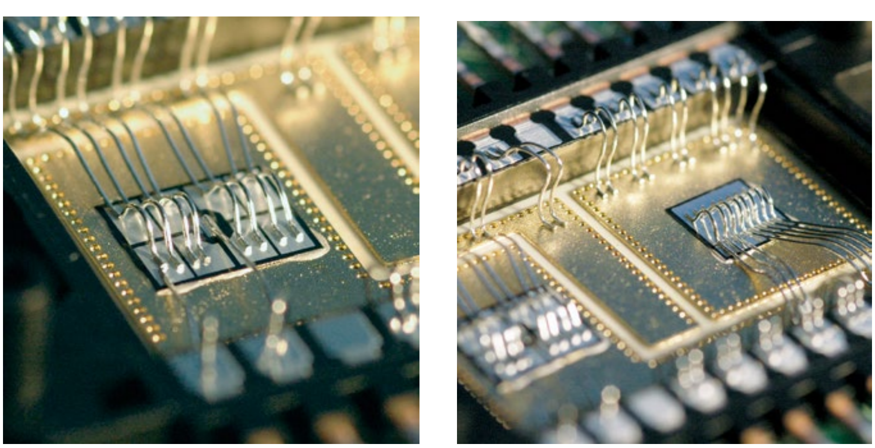

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Figure 4 > Detail views of the bonding of the IGBT (left) and the diode (right) with Polytec EC 242 electrically conductive adhesive.

Conclusion and outlook

The project results presented here have shown that, as a result of new developments in conductive adhesives, poten-

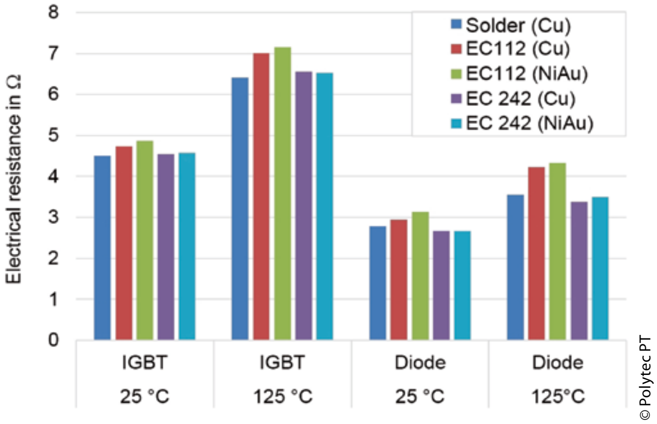

Figure 5 > Differential electrical resistance at IGBT and diode in the comparison between the solder and adhesive connection.

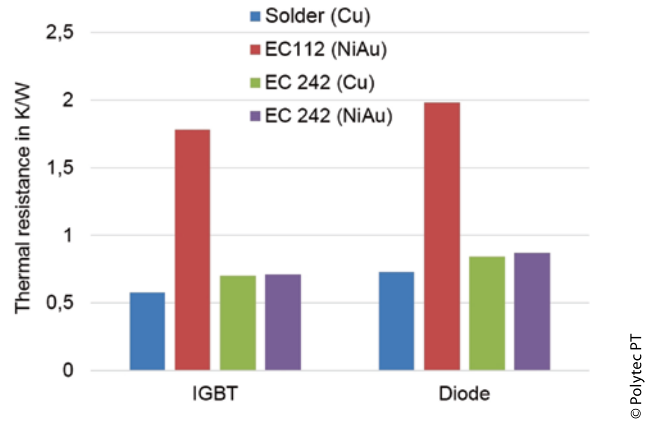

Figure 6 > Thermal resistances on IGBT and diode in the comparison between solder and adhesive bonding.

tial applications in the field of power electronics can be pursued, in addition to the proven application in microelectronics. The strength and durability of the adhesive bond is at least equivalent to that of a soldered bond, wherein the elasticity of the adhesive layer can be advantageous in the case of vibrational loads. The electrical conductivity of the adhesives allows the operation of power semiconductor devices even at current densities of up to 200 A/cm². Options for a further development of the adhesives lie with the thermal conductivity, which is generally somewhat above the conductivity of solder joints and is an important criterion for the reliability of the modules. When using adhesives, it therefore has to be verified whether sufficient thermal conductivity is available at the respective operating temperature. Power cycling tests for evaluating the reliability of the modules have also been performed. Overall, the project shows a significant advance in the development of adhesives for power electronics in comparison to the state of the art a few years ago. //

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