Integration of Silver Heat Spreaders in LTCC utilizing Thick Silver Tape in the Co-fire Process

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Abstract

The integration density in semiconductor devices is significantly increased in the last years. This trend is already described by Moore's law what forecasts a doubling of the integration density every two years. This evolution makes greater demands on the substrate technology which is used for the first level interconnect between the semiconductor and the device package. Higher pattern resolution is required to connect more functions on a smaller chip. Also the thermal performance of the substrate is a crucial issue. The increased integration density leads to an increased power density, what means that more heat has to dissipate on a smaller area. Thus, substrates with a high thermal conductivity (e. g. direct bonded copper (DBC)) are utilized which spread the heat over a large area. However, the reduced pattern resolution caused by thick metal layers is disadvantageous for this substrate technology. Alternatively, low temperature co-fired ceramic (LTCC) can be used. This multilayer technology provides a high pattern resolution in combination with a high integration grade. The poor thermal conductivity of LTCC (3 … 5 $W*m^{-1}*K^{-1}$) requires thermal vias made of silver paste which are placed between the power chip and the heat sink and reduce the thermal resistance of the substrate. The via-pitch and diameter is limited by the LTCC technology, what allows a maximum filling grade of approx. 20 to 25 %. Alternatively, an opening in the ceramic is created, to bond the chip directly to the heat sink. This leads to technological challenges like the CTE mismatch between the chip and the heat sink material. Expensive materials like copper molybdenum composites with matched CTE have to be used. In the presented investigation, a thick silver tape is used to form a thick silver heat spreader through the LTCC substrate. An opening is structured by laser cutting in the LTCC tape and filled with a laser cut silver tape. After lamination, the substrate is fired using a constraint sintering process. The bond strength of the silver to LTCC interface is approx. 5.6 MPa. The thermal resistance of the silver structure is measured by a thermal test chip (Delphi PST1, 2.5 mm x 2.5 mm) glued with a high thermal conducting epoxy to the silver structure. The chip contains a resistor and diodes to generate heat and to determine the junction temperature respectively. The backside of the test structure is temperature stabilized by a temperature controlled heat sink. The resulting thermal resistance is in the range of 1.1 K/W to 1.5 K/W depending on the length of silver structure (5 mm to 7 mm). Advantages of the presented heat spreader are the low thermal resistance and the good embedding capability in the co-fire LTCC process.

Key Words: LTCC, thermal management, thick silver tape, heat spreader

Introduction

Low Temperature co-fired Ceramic (LTCC) is commonly used as substrate for RF applications due to the high conductivity and pattern resolution of the conductors and the low loss of the dielectric layer [1-4]. Additionally, the LTCC technology captures new markets in the field of fluid and bio analytics due to their excellent corrosion resistance [5-8]. However, the low thermal conductivity of the LTCC material (around 3 to 5 W/m*k) limits their usage for power applications. Thermal vias are added to locally increase the thermal conductivity. Alternatively a cut-out through the LTCC allows the bonding of the chip directly to the heat sink [9-11]. These designs lead to technological challenges like the CTE mismatch between the chip and the heat sink material. Thus, expensive heat sink materials with matched CTE are utilized as MoCu or WCu. An alternative approach is to cool down the device by a coolant which is guided through fluidic channels inside the LTCC device [12-15].

In [16] the integration of a proprietary silver tape in LTCC for thermal management purpose is reported. The integration of silver tape in the LTCC provides paths with a high thermal conductivity. Hence, the thermal resistance of the critical path between power chip and heat sink can be reduced. In the presented investigation a commercially available silver tape is integrated in the LTCC during the co-fire process to form a through substrate heat spreader. Figure 1 shows a schematic cross section of the silver head spreader.

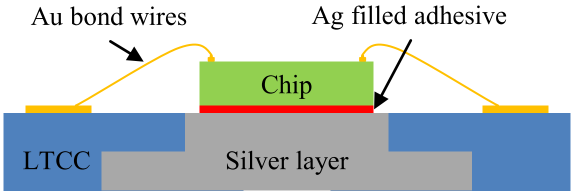

Figure 1: Schematic cross section through the silver heat spreader design, the chip is bonded directly to the silver structure.

The thermal performance of heat spreader is investigated and compared with common thermal management solutions. Additionally, the interface between the LTCC and the silver structure is investigated for leaks and the bond strength is measured.

Fabrication of the silver heat spreader in LTCC DuPont 951 Green Tape™

The silver tape comprises organics filled with silver particles. A filling grade of more than 90% is measured utilizing energy dispersive X-ray spectroscopy (EDX) analysis. The tape is sintered at temperatures higher than 600°C in order to form a crystalline structure.

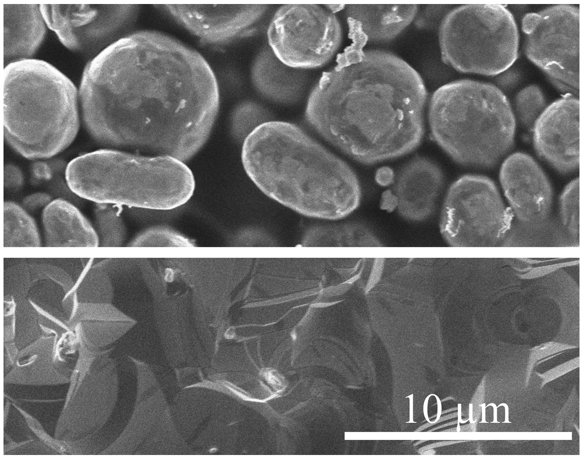

Figure 2: REM image of silver tape before (top) and after sintering (bottom). Unsintered material has a particle size distribution of 0.7 µm to 9 µm. Material sintered at 875°C shows crystalline structure.

Figure 2 shows the REM image of the silver tape before and after sintering. A z–shrinkage of 35% is measured utilizing a horizontal pushrod dilatometer (NETZSCH DIL 402 E) when sintered with the recommended LTCC DuPont 951 sintering profile. The sheet thickness of the silver tape and the LTCC tape matches (254 µm), thus they can be easily compared. Openings and small plates are structured by laser cutting (Q-switched Nd:YAG laser at a wavelength of 355 nm by LPKF Laser & Electronics AG) into single LTCC tapes and the silver tape respectively. The heat spreader structure comprises two laser cutted LTCC sheets and two small silver plates (cf. figure 3). The stacked and aligned tapes are isostatically laminated at a pressure of 210 bar and a temperature of 70°C. The substrate is fired utilizing a pressure assisted constraint sintering process (1.7 kPa, 875°C for 30 min).

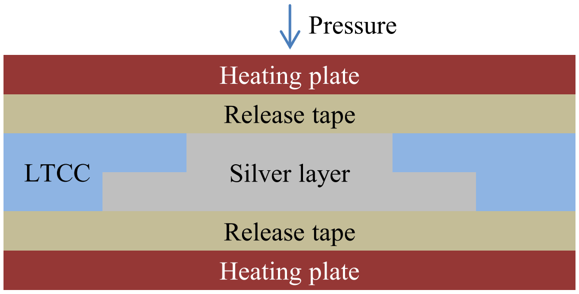

Figure 3: Schematic cross section through the sintering approach. Release tape is laminated to the stack to constrain the substrate during sintering.

The fired LTCC module has dimensions of 18 x 18 x 0.32 mm³. The length of the silver heat spreader is 3 mm in the top layer and varies from 5 mm to 7 mm in the bottom layer. In figure 4 the cross section through the right corner of the fabricated heat spreader is depicted. Slightly pull-back of the silver structure from the surrounding LTCC can be observed.

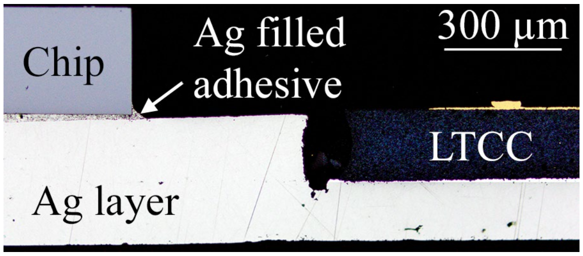

Figure 4: Detailed cross section through the right corner of the fabricated silver heat spreader. The chip is bonded with silver loaded adhesive to the silver structure.

Evaluation of thermal performance

The thermal performance is evaluated by the measurement of the steady-state thermal resistance. A thermal test chip (PST1-02/5PU by Delphi) is bonded with silver filled adhesive (λ = 60 W/mK) directly to the silver structure. The chip has an active area of 6.25 mm² and contains a planar resistor for resistive heating (*P*) and temperature sensor (T_j). The module is placed on a temperature controlled heat sink to get stable measuring conditions. The heat sink consists of a Peltier element, a water cooler and a copper heat spreader. The power of the Peltier element is regulated by a PID controller (TED4015, Thorlabs INC., stability ± 1 mK), which uses the heat spreader temperature as present value. The heat spreader temperature (T_{GND}) is obtained from a thin-film RTD (Pt1000, ± 100 mK accuracy at 22°C) which is integrated in the copper heat spreader 1 mm below the surface. Figure 5 shows the schematic cross section of the measurement arrangement.

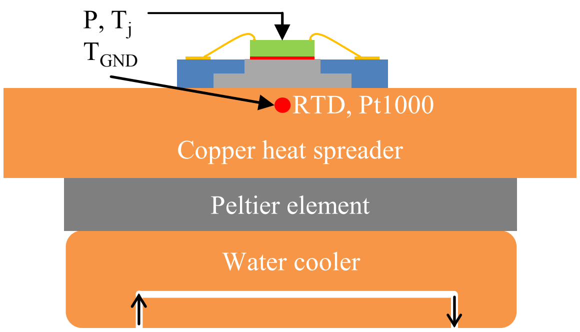

Figure 5: Schematic cross section through the measurement approach. The module with bonded thermal test chip is placed on a temperatur controlled heat sink.

A thermal load generated by resistive heating increases the junction temperature of the thermal test chip. At the point of thermal equilibrium the thermal resistance is calculated by (1).

$$R_{th} = \frac{(T_j - T_{GND})}{P} \qquad (1)$$

The thermal resistances of three silver heat spreaders are measured. Three alternatives for thermal management are investigated utilizing the same approach and test chip. This allows a comparison of the solutions. For this purpose a module with an array of 36 thermal vias made of silver paste (diameter: 250 µm, pitch: 500 µm) is fabricated and assembled with the thermal test chip. A second module allows the direct placement of the chip in a cavity. Here the test chip is bonded on a 1.5 mm thick Mo30Cu heat spreader utilizing low temperature silver sintering.

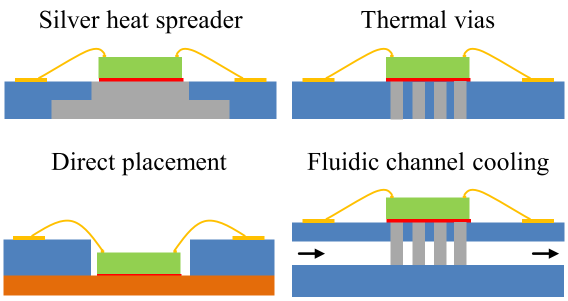

Figure 6: Schematic cross section through different cooling solutions.

The active cooling of the module with integrated fluidic channels is presented in previous works and compared to common thermal management solutions [15]. In this design fluidic channels integrated in the LTCC guides a coolant through the module, what dissipates the heat out of the module. The chip is placed on an array of 36 thermal vias which transfers the heat into the fluidic channel. Water with a constant volume flow of 200 ml/min was used as coolant. The calculation of the thermal resistance was based on the temperature difference between junction and fluidic inlet. In figure 7 the thermal resistance of all modules is compared. An exponential relation between the length of the silver heat spreader and the thermal resistance is observed. It can be assumed, that the heat spreading angle doesn't increase significantly by increasing the spreading length above a specific value. This length strongly depends on the chip length and the heat spreader thickness. Thus, the effective thermal resistance won't be affected above this point. The minimal thermal resistance is 1.2 K/W for the investigated chip with a length of 2.54 mm which is nearly 4 times lower than the thermal resistance of the thermal via approach.

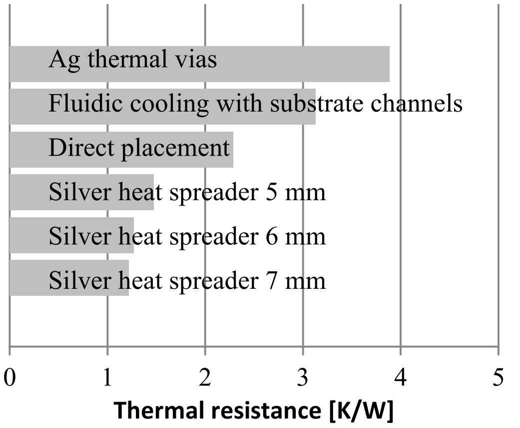

Figure 7: Junction to case / junction to fluid resistance of common thermal management solutions in LTCC compared to the silver heat spreaders, ordered by size.

Testing for leaks and evaluating bond strength

The leak tightness of the bond interface is tested by a helium leak test utilizing an evacuated chamber below the LTCC substrate [17]. For this purpose the LTCC module is bonded with vacuum-tight glue on a vacuum adapter which is depicted schematically in Figure 8. The measurement arrangement is evacuated to 5 x 10^{-4} mbar through an opening in the adapter. A helium enriched atmosphere is generated around the chamber at atmospheric pressure. A helium sensitive mass spectrometer (SmartTest by Pfeifer Vacuum GmbH) detects helium which flows through leaks in the bond interface into the chamber (cf. figure 8). All fabricated bond interfaces show a leak rate over 5 x 10^{-5} mbar·l/s, which implies that the interface between the LTCC and the silver tape is not gas tight. Nevertheless, the bulk silver tape showed leak rate below 5 x 10^{-10} mbar·l/s, when tested with the same approach. Therefore, it can be assumed, that the silver material itself is densely sintered.

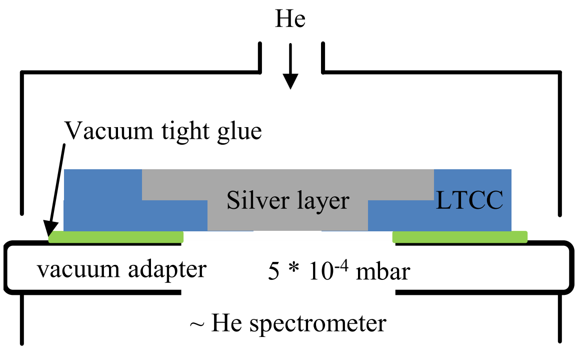

Figure 8: Leak test with a He sensitive mass spectrometer (vacuum method). The test sample is evacueted to 5 x 10^{-4} mbar and helium enriched atmosphere is generated arround.

The bonding strength is measured by a tension test. Therefore, silver plates (10 mm square) are buried into a LTCC substrate. Different silver layers (bonding agent A and B) are screen printed on the LTCC layers, to enhance the bond strength between the LTCC-silver plate interfaces. The substrate is cutted in 10 mm square pieces after firing. In the next step, retaining pins are glued to the bonded assembly. A tensile force is applied to the retaining pins by a tensile testing system (Z010 by Zwick GmbH & Co. KG) and the tensile force is measured. The testing approach allows tensile forces up to 2 kN (maximum tensile strength 8.8 N/mm² for the tested area). Figure 9 shows the test approach. The mean test results and the deviation are shown in Table 1. The bond interface between the LTCC and the silver plate fails before the test limit was achieved. Crack developing in the LTCC could be also observed.

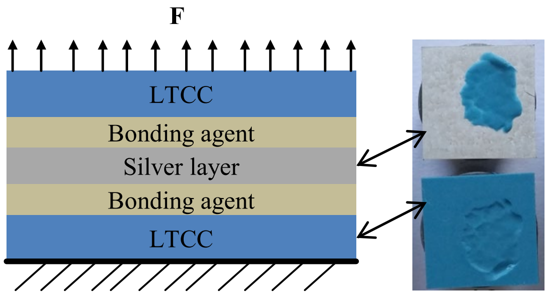

Figure 9: Left: schematic view of the approach for measuring the tensile strength, retaining pins are excluded. Right: sample without bonding agent after test, the weak point is the interface between the silver tape and the LTCC, cracks occurs also in the LTCC

It is very likely that this is caused by induced thermal stress during the cooling step in the sintering process. This stress is caused by the CTE mismatch between the silver plate and the LTCC. The highest tensile strength is achieved with bonding agent A accompanied by a high deviation. The samples, fabricated without a bonding agent show a slightly lower tensile strength with a reduced deviation. Further investigations have to clarify the reason for the high deviation of the test samples with bonding agent A.

Table 1: Measured tensile strength of the LTCC – silver tape interface. The highest bonding strength is achieved with bonding agent A accompanied by a high deviation.

Bonding agent	Tensile strength [MPa]	Deviation [MPa]
Without	5.6	1.1
Ag Paste A	8.5	7.9
Ag Paste B	1.6	1.0

Conclusion

A thick silver heat spreader is integrated in a LTCC substrate during the co-firing process. The bonding strength evaluated by a tension test is 5.6 MPa for the samples without a bonding agent. The higher tensile strength of the samples with bonding agent A is accompanied by a high deviation. Hence, further works have to take care about the reason for the high deviation. The gas tightness of the bond interface could not be affirmed, but the silver tape seems to be densely sintered. The thermal resistance is measured utilizing a thermal test chip and a temperature controlled heat sink. With a thermal resistance of 1.2 K/W the heat spreader is sufficient for many applications in the middle to lower power segment.

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