Advanced DBC - Highly Reliable and Conductive Copper Ceramic Substrates

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Abstract

So far Direct Bonded Copper (DBC) substrates have been the standard for power electronics. They provide excellent electrical and thermal conductivity at low cost. Weaknesses of DBC technology are the inevitable warpage and the relatively low reliability under thermal cycling. The low reliability poses a significant hurdle in particular for automotive applications with high lifetime requirements. Thick Print Copper (TPC) substrates with low warpage and excellent reliability overcome these weaknesses, but also provide a reduced conductivity at a higher cost. We present two thick-film/DBC hybrid technologies which combine the best properties of DBC and TPC: excellent conductivity, low cost, reduced warpage and excellent reliability.

1 Introduction

Thick-film technology for electric circuits is always used when a circuit is subject to harsh environmental conditions, such as aggressive chemicals, high and low temperatures, high humidity, mechanical stress, and strong temperature variations [1]. Due to the high reliability and resistance to adverse conditions combined with excellent thermal and electrical properties thick-film circuits are well established in a wide range of industrial applications covering fuel tank sensors, solar cells, headlights for cars and engine controllers [e.g. 2, 3]. For power electronic and LED substrates we introduced Thick Print Copper (TPC) in earlier publications [4, 5]. We could show, that TPC provides higher reliability, less warpage and superior design freedom compared to the current standard technology Direct Bonded Copper (DBC). At the same time DBC has a 30 % lower thermal and electrical resistance and a cost advantage for standard applications. In this paper, we introduce two thick-film/DBC hybrid technologies for power electronic substrates combining the advantages of TPC and DBC in one substrate.

We call the first hybrid substrate technology “Paste Enhanced Directed Bonded Copper” (PE-DBC). PE-DBC substrates consist of a standard DBC on alumina with thick-film paste reinforced copper edges. The insulating thick-film paste is applied by dispensing around the copper structures and firing at temperatures above 500 °C. During the firing the thick-film paste sinters and forms strong bonds to the alumina substrate as well as to the copper layer. This reinforces the interface between copper and ceramic at the critical edges of the copper structures. The reinforcement significantly increases the reliability of the DBC substrates without significant cost increase. We demonstrate the improvement by thermal shock testing PE-DBC substrates in comparison to standard DBC substrates.

The second technology “Paste Bonded Copper” (PBC) achieves an even higher reliability than PE-DBC and the additional benefit of a significantly reduced warpage. A PBC substrate is created by sintering copper foils on top of TPC substrates. For PBC we demonstrate the outstanding reliability, the excellent bond quality and the low warpage variation upon heating.

2 Paste Enhanced Direct Bonded Copper (PE-DBC)

PEDBC-substrates consist of standard DBC on alumina substrates with reinforced edge structures for an improved reliability.

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2.1 Manufacturing Process

The PE-DBC production process starts with a standard DBC process. Consecutively the etched DBC is enhanced in a thick-film process consisting of the following three steps:

1. Applying an insulating thick-film paste on the alumina around the copper structures for example by dispensing (see Fig. 1).
2. Drying the paste in air at ~120 °C for 10 min.
3. Firing the substrate in nitrogen at temperatures above 500 °C.

The nitrogen firing prevents the copper layer from oxidizing. The used insulating paste is lead-free.

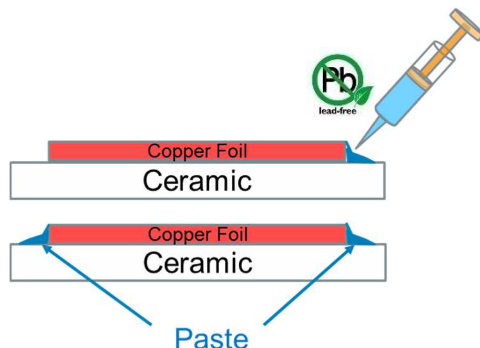

Fig. 1: Dispensing of the paste around the copper structures. It is important to avoid any gap between paste and copper. The paste can be printed in a way, so that it fully surrounds the copper structures or only the most critical parts.

2.2 Reliability

We tested the PE-DBC parts in comparison to standard DBCs with the same copper pattern. The copper thickness is 300 µm, the alumina thickness 630 µm. The test procedure of the thermal shock test is illustrated in Fig. 2. The substrates are kept for 15 min at -40 °C, transferred to a +150 °C chamber within 15 s and kept there for another 15 min, before transferred back to the -40 °C chamber in 15 s. For standard DBCs we observed conchoidal fracture at the copper layer edges starting after 100 thermal shock cycles. The PE-DBC substrates did not show any delamination in Surface Acoustic Microscopy (SAM) before 2000 cycles using standard DBCs without dimples on 96 % alumina.

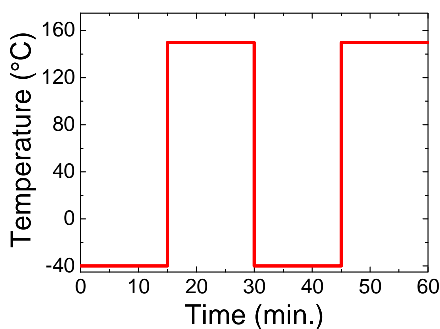

Fig. 2: Temperature Profile of the thermal shock test. The transfer time between the -40 °C chamber and the +150 °C is 15 s.

An optical image and a SAM measurement of a substrate with a paste enhanced Cu structure and a not enhanced Cu structure after 2000 thermal shock cycles are depicted in Fig. 3. The enhanced part is practically unchanged even after 2000 cycles.

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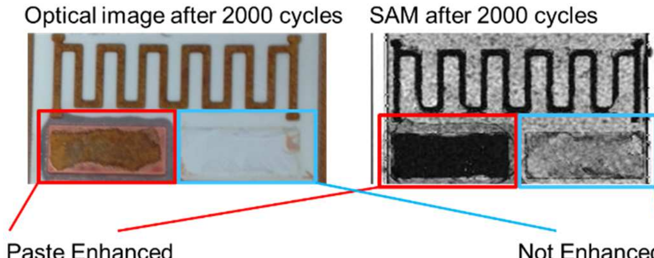

Fig. 3: Optical image (left) and SAM measurement (right) of a DBC substrate with a paste enhanced Cu structure (within the red rectangle on the left) and a not enhanced Cu structure (within the blue rectangle on the right) after 2000 thermal shock cycles. The conchoidal fracture below the not enhanced part is clearly visible, while the enhanced part is practically unaffected by thermal cycling.

3 Paste Bonded Copper (PBC)

Paste Bonded Copper (PBC) substrates are TPC substrates with a Cu foil sintered on top of the thick-film layer.

3.1 Manufacturing Process

The processing of PBC substrates starts with a standard TPC process (first three boxes in Fig. 4):

1. Copper paste is screen printed on both sides of a ceramic. Fine structures, which can serve as logic circuit can be included.
2. The paste is dried in air for 10 min at 120 °C.
3. The substrate is fired in nitrogen above 500 °C

After the TPC part is finished the copper foils are sintered on the TPC substrate (last three boxes in Fig. 4):

4. The Cu foils are stacked on top and on the bottom of the TPC substrates, the logic circuit part is left blank.
5. The stack in fired in a nitrogen furnace at temperatures above 800 °C.
6. The desired structure is etched into the Cu layer as for standard DBCs.

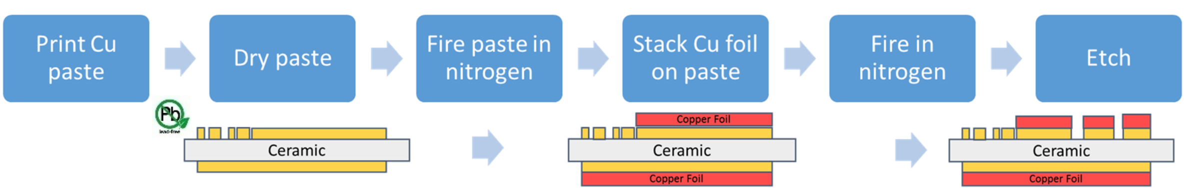

Fig. 4: Flow chart of the PBC process. The first three boxes describe the standard TPC process. The following three boxes the sintering of the Cu foils on top of the thick-film layer and the final etching.

3.2 Bonding Interface

We analyzed the interfaces between ceramic and copper paste and between copper paste and copper foil by SEM (Fig. 5). The interface between paste and foil cannot be identified due to the dense sintering of the material. The interface between ceramic and copper is void free. This is very important for the reliability and the partial discharge properties of the substrates. Within the copper layer a few small voids can be seen, which can be neglected and have no influence on the discharge properties.

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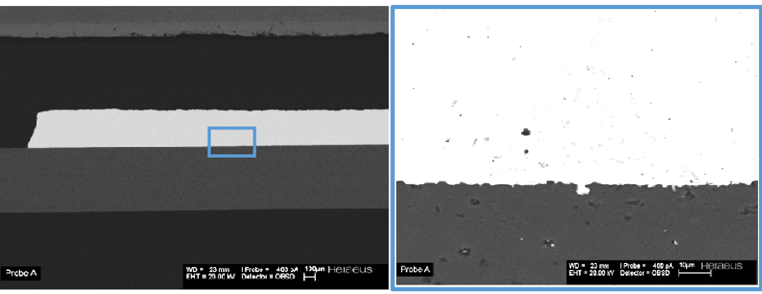

Fig. 5: Cross section of a PBC substrate. The bright layer is the copper, the light dark layer below the alumina. On the right side a detail image of the interface is displayed. No voids between copper and ceramic can be detected.

3.3 Reliability

2”x2” PBC substrates with a total copper thickness of ~350 µm and an alumina thickness of 630 µm are subjected to the same thermal shock cycling as described in chapter 2.2. An optical image of the substrate after 2000 thermal shock cycles is depicted on the left in Fig. 6. The substrate is characterized by SAM initially and after 600 and 2000 cycles. Initially it can be seen, that the edges of the copper foil are not perfectly bonded to the thick-film layer. This is due to the not optimized processing at that time. The SAM images after 600 and 2000 thermal shock cycles demonstrate, that no additional delamination occurs.

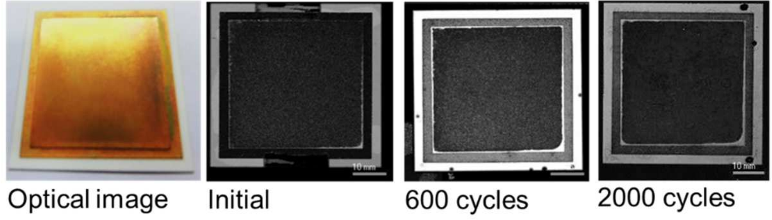

Fig. 6: Optical image after 2000 thermal shock cycles, initial SAM, SAM after 600 and SAM after 2000 thermal shock cycles (from the left to the right). No additional delamination occurs even after 2000 thermal shock cycles.

3.4 Adhesion

The adhesion of the PBC technology is tested on 4x4 mm² Cu foils. A shear tester is used, measureing the maximum force of a chisel to peel off the copper (Fig. 7 top). The maximum force of PBC in comparison to DBC is depicted in Fig. 7 (bottom). More than 80 % of the shear force of DBC is achieved by PBC.

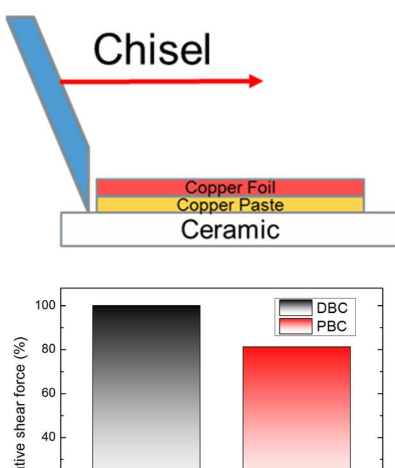

Fig. 7: Schematic of the shear test (top) and shear force results (bottom). The shear tester measures the maximum force while the chisel is shearing-off the copper foil.
The shear forces of PBC are more than 80 % of the DBC values. This is more than sufficient for all practical purposes.

Fig. 8 shows an optical image of the sheared-off Cu foil on top of a continuous TPC layer. The failure mode is partly within the ceramic, which shows, that neither the copper/ceramic nor the paste/foil interface are weak spots of PBC.

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Fig. 8: Optical image of a sheared-off copper foil. The image shows, that the failure occurs at least partly within the ceramic demonstrating the good bonding between copper paste and ceramic as well as between copper paste and copper foil.

3.5 Warpage

The warpage of 2”x2” substrates with a Cu thickness on both sides of ~300 µm and an alumina thickness of 630 µm is analyzed by Moiré shadow analysis. Moiré shadow analysis can measure the warpage at different substrate temperatures []. A low initial warpage and a low warpage variation are desired to avoid excessive stress on solder or sinter joints to baseplates and dies.

The warpage of TPC, DBC and PBC substrates are measured at room temperature, at 50 °C, 100 °C, 150 °C and 200 °C. The measured warpage is displayed in Fig. 9. As already published before [], the warpage of TPC is below that of DBC. PBC substrates have a warpage variation between DBC and TPC.

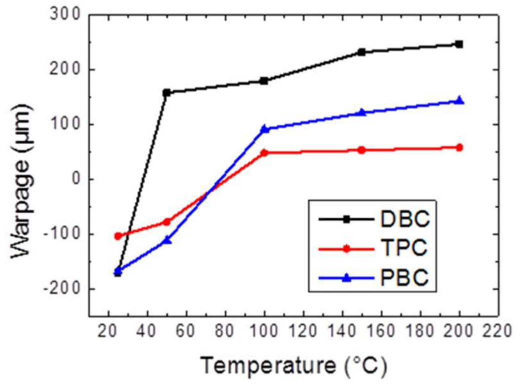

Fig. 9: Warpage of DBC, TPC and PBC substrates between room temperature and 200 °C. TPC has the lowest warpage variation, DBC the highest and PBC is in the middle.

4 Comparison

In Table 1 the key properties of PE-DBC and PBC are summarized and compared. Both technologies are based on proven and mass production suitable processes and lead-free materials. PBC has the additional advantages of a low warpage and the ability to combine logic and power circuits on one substrates without additional processes. In comparison to TPC the new technologies PE-DBC and PBC have the advantages of a higher thermal and electrical conductivity (same as for DBC) and lower cost at high copper thicknesses.

	PE-DBC	PBC
Proven up to 2000 thermal shock cycles (-40 °C; +150 °C)	Yes	Yes
Reduced Warpage	No	Yes
Mass production suitable processes	**Yes**	**Yes**
Low inductance layouts	**Yes**	**Yes**
Logic + power fineline	**No**	**Yes**
Lead-free	**Yes**	**Yes**

Table 1: Key parameters of PE-DBC and PBC. Both provide an excellent reliability with no delamination up to 2000 thermal shock cycles. PBC offers the additional advantages of a reduced warpage and the possibility to combine logic and power circuits on one substrate.

5 Summary

In this paper we presented two new substrate technologies for power electronics. Both are hybrid technologies of Direct Bonded Copper (DBC) and thick-film technology and combine the advantages of both technologies. Paste Enhanced DBC (PE-DBC) and Paste Bonded Copper (PBC) were demonstrated

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to have excellent reliability under thermal cycling, excellent conductivity due to the solid copper foil, to use only mass production suitable processes and high adhesion at low cost. PBC has the additional advantages of a low warpage variation upon heating and its ability to combine logic and power circuit on one substrate. This makes PE-DBC as well as PBC ideal solutions for automotive power electronic applications with high conductivity and reliability requirements.

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