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Diamond Composites for Power Electronics Application

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Abstract. In view of power electronics applications, baseplates made from metal diamond composites have been manufactured and characterised. The surface contours of the baseplates were measured during thermal loads up to 180°C starting at room temperature with help of the TherMoiré technique. X-ray analysis investigation was performed to detect porosity and local inhomogeneities of the baseplates. Al- and Cu-based diamond composite baseplates were Ni-plated and used for manufacturing of 3.3 kV IGBT modules. The solder layer between AlN AMB (active metal brazing) substrates and baseplates was investigated by ultrasonic and X-Ray analyses. Thermal resistance of the manufactured IGBT modules was characterised and compared to that of IGBT modules with AlSiC or Cu baseplates. The influence of thermal cycling on the solder layer and thermal resistance of the manufactured module was investigated.

Introduction

With increasing concentration of energy dissipation in electronic components heat conduction becomes a decisive design criterion for high power electronic modules like Insulated Gate Bipolar Transistor (IGBT) modules [1, 2]. The changes in ambient temperature and moreover the heating during service generate thermally induced stresses between the materials of a power electronic module due to their different coefficient of thermal expansion (CTE). Thermal fatigue of the system solder between an AMB substrate and a baseplate is enhanced by thermal cycles causing crack propagation, which reduces the heat transfer and thus the electric efficiency and service life time of the module. One of the solutions is the application of metal matrix composites containing high-volume fractions of ceramics, diamond or carbon particulates or fibres as a material for the baseplate.

New metal matrix composites were produced with the aim of obtaining high thermal conductivities (TCs) and reduced CTE by reinforcing with diamonds via gas pressure infiltration (GPI) or squeeze casting (SC) [3]. In the power electronics applications, the most promising materials for a baseplate in IGBT modules are Cu- and Al-based diamond composites. In spite of the fact that Ag-based diamond composites possess significantly higher TC of up to 920 W/(m·K) [4] than Al- or Cu-based diamond materials, they are not applicable for a baseplate in an IGBT module because of the high costs of Ag-based diamond composites.

This paper is devoted to the characterisation of developed Al- and Cu-based diamond composites and compares their properties with the standard baseplate materials, namely Cu and AlSiC. In view of solder fatigue, a lifetime model of the system solder layer is given that compares the dissipated work per thermal cycle for different baseplate materials.

Material properties of diamond composites

In the framework of ExtreMat project, different properties of diamond composites were investigated and compared with industrial AlSiC. The composite materials were produced by two different liquid metal infiltration techniques – GPI and mechanically assisted infiltration, namely SC: GPI was used for AlSiCD and CuBCD, and SC for AlCD. For the characterisation, both small samples and baseplates with a size of 137 x 127 x 5 mm^3 (typical for traction applications) were taken.

Mechanical properties. Mechanical properties of diamond composites with pure Al (AlCD) or AlSi (AlSiCD) matrix and industrial AlSiC were investigated by four-point bending tests at room temperature. In contrast to AlSiC, the AlSiCD and AlCD specimens were found to be strongly deflected at the breaking load and yielded already at low loads. In comparison with AlSiC and AlSiCD, the investigated AlCD was more ductile because of the matrix material, pure Al. The two-parameter Weibull statistics was applied to the ranked cumulative probabilities of the maximum flexural stress data [5]. The Weibull flexural modulus β indicates the homogeneity of material. The more heterogeneous the material, the smaller β is, because the specimen fracture occurs at very different loads. Table 1 lists values of the characteristic flexural strength σ_0, the Weibull flexural modulus β and Young's modulus of AlSiC and diamond composites. The industrial AlSiC appears to be stronger and more homogeneous than diamond composites, since both AlCD and AlSiCD show 3 times lower flexural strength and lower Weibull flexural modulus than those for AlSiC. The Young's modulus of AlSiC and diamond composites is the same and is about 200 GPa.

Composite	Characteristic flexural strength σ_0, [MPa]	Weibull flexural modulus, β	Young's modulus, [GPa]	Thermal conductivity TC, [W/(m·K)]	Coefficient of thermal expansion CTE, [ppm/K]
AlCD	97	9.9	202	120 – 540	7 – 16
AlSiCD	102	4.4	211	440 – 520	7 – 10
CuBCD	-	-	-	470 [6]	6.7 [6]
AlSiC	344	17.3	207	200 [2]	7 [2]

Table 1: Mechanical and thermal properties of Al- and Cu-based diamond composites compared to AlSiC

Thermal properties. TC of the developed composites was determined on the small specimens with the help of laser Flash method. CTE was investigated by means of the measurement of the linear thermal expansion $\Delta L(T)/L_0$ with a dilatometer. In view of reliability, the bonding of the diamond particles to the metal matrix is an important issue, which was tested by thermal cycling in a two chamber oven. Thermal cycling tests of up to 1000 cycles at -55°C / +150°C were performed and TC and CTE of the specimens have been measured. The resistance to corrosion was investigated with the help of pressure cooker tests carried out at 121°C and 2 bar for 168 hours. The thermal properties of the diamond composites strongly depend on the diamond quality and the composite processing (see Table 1). According to the tests on the small specimens, thermal cycling impaired TC and CTE, especially if the interface between a reinforcement component and a matrix was not optimal. That led to reduction of the thermal conductivity by about 35% of value and increase of CTE by 20% after 1000 cycles, whereas a stronger bonding between the reinforcement and matrix resulted in reduction of the thermal conductivity by 10% upon thermal cycling. Moisture generated during pressure cooker test resulted in the formation of aluminium hydroxide at the surface of Al-based composites. However, this reaction was restricted only to the surface.

Diamond composites in IGBT modules

To avoid overheating of some chips of an electronics module because of local high thermal resistance, heat sink materials should be homogeneous and have small warpages.

To characterise the homogeneity of material distribution in baseplates, X-ray analysis was carried out on both Al- and Cu-based diamond composites. The investigated Al-based diamond plates produced by GPI and SC had areas with pores inside the matrix, which were partly through-going. In the case of AlCD and AlSiCD baseplates the shrinkage porosity was found in the form of holes on the surface and in the volume. This problem of porosity appeared only during production of large area pieces, such as baseplates, because of a non-uniform solidification of the infiltrated metal. The presence of pores inside the Al-based diamond composite resulted in large differences of the thermal conductivity within the same baseplate from 480 W/(m·K) to 260 W/(m·K) that would significantly impair the reliability of a module. As to the diamond composite with CuB matrix (CuBCD), no presence of pores or other inhomogeneities was detected by X-ray analysis.

To investigate the reversibility of the plate's warpage after heating, the TherMoiré analysis was performed at different temperatures up to 180°C on the AlCD, AlSiCD and CuBCD baseplates. The maximum warpage of 100 µm of the plates in as-received condition at room temperature was observed on the AlCD plates and the plates had a concave form. The higher temperature, the more pronounced the baseplate's warpage was. Because of yielding caused by heating during the measurements all the investigated AlCD, AlSiCD and CuBCD plates revealed after the test a residual deformation of up to 25 µm.

For the first tests, AlSiCD and CuBCD composites were selected as a baseplate material for a 3.3 kV IGBT module. Prior to soldering of the AMB substrates, the baseplates were Ni-plated. The modules were characterised by ultrasonic and X-ray analyses in view of the quality of the system solder layer. The surface roughness and the presence of open pores in the AlSiCD baseplate have significantly worsened the Ni-plating and, as a consequence, the quality of the solder layer. There was a large air gap without solder at the place near the open pores that significantly increased the thermal resistance locally. In contrast to the AlSiCD, no defects were found in the system solder of the IGBT modules with the CuBCD baseplates.

To compare the efficiency of IGBT modules, thermal resistance of the modules with the following baseplates was measured: CuBCD, Cu and AlSiC. The module produced a power dissipation of 1.6 kW at a nominal load current of 400 A. The nominal current was switched-on until the thermal equilibrium of a system was reached and then the current was switched-off. The measured collector-emitter voltage of IGBT chips depends on the temperature and it can be converted to a chip temperature after calibration. The collector-emitter voltage was measured at the measuring current of 0.04 A. To exploit the benefit of baseplates with high thermal conductivities, an open water cooler was selected providing very good cooling. The high turbulent flow of water leads to a high heat transfer coefficient of this cooler. The temperature difference ΔT_{ja} was measured between the chips and the cooling water. According to the obtained results, the thermal resistance of the test module with CuBCD is lower than that with standard baseplates (see Table 2), leading to lower chip's temperature.

Baseplate material	Cu	AlSiC	CuBCD, before thermal cycling	CuBCD, after thermal cycling
Rth_{ja}, [K/W]	0.0283	0.0318	0.0268	0.0281

Table 2: Thermal resistance Rth_{ja} of 3.3kV IGBT modules with different baseplates

To investigate the influence of the passive cycling on the system solder, thermal cycling was performed on the IGBT module at the following conditions: -40°C / +125°C, 20 minutes of a holding time at each temperature, and 930 cycles. Crack formation in the system solder was detected by means of ultrasonic analysis after the thermal cycling. Furthermore, warpage of the CuBCD baseplates increased and that resulted in changing of cooling conditions during the thermal resistance measurements. For this reason, the other open cooler was used for the characterisation. The observed defects in the system solder led to a higher thermal resistance of the module.

Lifetime modelling of soft solder layers in IGBT modules

FEM simulations with planar model [7] have been performed to estimate the qualitative influence of different baseplate materials on the lifetime of a power module due to solder fatigue. The material properties were all linear elastic, isotropic except the solder layers which were described by the viscoplastic Anand model. As a boundary condition, active cycles were simulated, with a power loss of 150 W per chip, 6 seconds on and 6 seconds off. As a cooling, a heat transfer coefficient of 5000 W/(m^2·K) located on the bottom of the baseplate material was chosen. The dissipated energy density per power cycle Δw_{pl} was selected as a damage criterion for the solder. The dissipated energy density per power cycle in the Sn63Pb37 system solder strongly depends on CTE of a baseplate material (see Fig 1). The minimum on the curve, CTE of 5 ppm/K, represents the best adaption in the power module in terms of CTEs of baseplate and ceramic substrate. As to influence of TC, the dissipated energy density per cycle is reduced by about 15% by application of CuBCD baseplate instead of AlSiC. As a consequence, a longer lifetime for CuBCD module is expected. The influence of Young's modulus on the dissipated energy density per cycle is not so pronounced as that of CTE and TC, since there is a very small difference between an IGBT modules with Cu, AlSiC and CuBCD baseplates. The stiffer the baseplate material, the higher the dissipated energy density in the solder is.

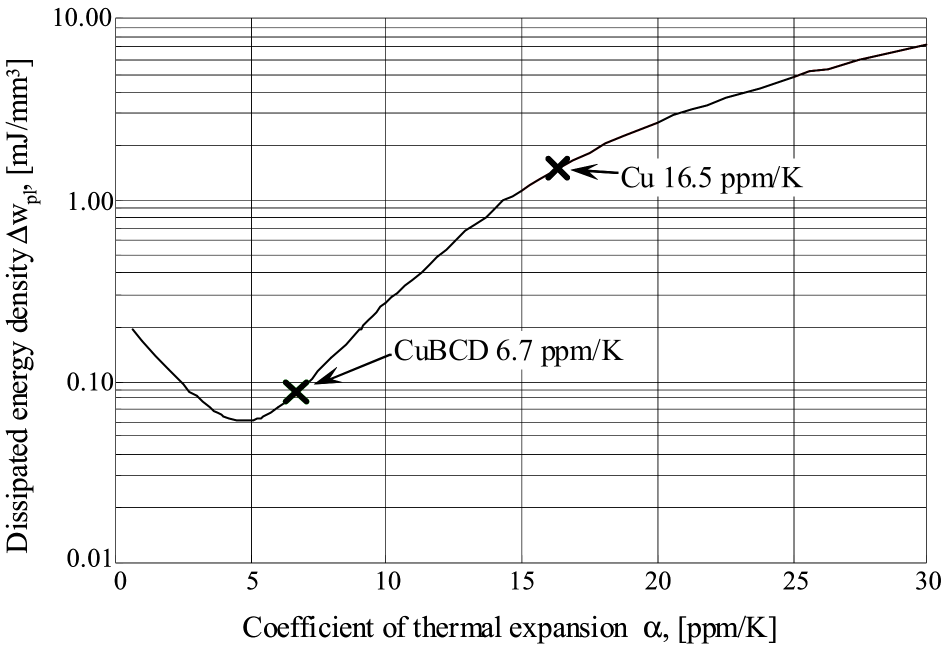

Fig. 1: Variation of dissipated energy density per cycle with coefficient of thermal expansion

Three material parameters influence the damage criteria of solder and, therefore, the lifetime of the whole power module [8]. The coefficient of thermal expansion is the most important factor, followed by the thermal conductivity and the Young's modulus. Power cycle tests carried out along with the simulations make it possible to estimate the final lifetime of the power module [9].

Conclusions

In the framework of ExtreMat project, diamond composite materials AlCD, AlSiCD and CuBCD were characterised and tested as a baseplate of a power electronics module.

- The Young's modulus of investigated Al-based diamond composites is of the same order as that of AlSiC. However, the diamond composites deform plastically already at low loads and have significantly lower flexural strength, in comparison with industrial AlSiC. Therefore, a pronounced bending of the diamond baseplates was observed due to thermal-induced stress.
- An optimal interface between diamonds and the metal matrix leads to high thermal conductivity, low CTE and high stability against thermal cycling.
- Shrinkage porosity in the baseplates made from AlCD and AlSiCD impairs significantly the properties of the baseplates. The through-going pores and the open pores on the surface lead to large voids or gaps in the solder layer.

- Thermal resistance of the 3.3 kV IGBT module with the CuBCD baseplates is lower than that with standard baseplates. However, the standard thermal cycling results in the crack formation in the system solder and strong bending of the baseplate.
- According to FEM simulations, CTE of a baseplate material plays the most important role for the module reliability. The next parameters to consider are its thermal conductivity and Young's modulus.

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