Ultra High Conductivity Diamond Composites

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Abstract

Thermal management is one of the critical aspects in the design of highly integrated microelectronic devices. The reliability of electronic components is limited not only to operating temperature but also by the thermal stresses caused during the operation. The need for higher power densities calls for use of advanced heat spreader materials. A copper diamond composite has been developed with high thermal conductivity (λ) and tailorable coefficient of thermal expansion (CTE). Copper diamond composites are processed via gas pressure assisted infiltration with different copper alloys. Emphasis has been placed on the addition of trace elements in deisgning the copper alloys to facilitate a compromise between thermal conductivity and mechanical adhesion. The interfaces between the alloy and the diamond are related to the thermal properties of these copper composites.

Keywords : Diamond composites, copper alloys, heat spreader, thermal management, pressure infiltration

1. Introduction

Thermal management and thermal stresses are critical in high-power laser diode packaging, LED, and microprocessor units [1]. Reliability and long life time calls not only for high λ but also CTE matching to that of semiconductors. To use a material in electronic packaging its CTE should be compatible with that of the semiconductor, i.e CTE between 4-7 ppm/K. The trick is to use reinforcement material with lower CTE and by varying the volume fractions of the reinforcement, the CTE can be tailored to that of the specific semiconductor and application. Among all the reinforcements diamonds are attractive as they have high thermal conductivity (1000-1500 W/m.K for commercially available industrial diamonds) and the ever decreasing prices bring them closer to the market realization. Metal diamond composites have been processed using high pressure and high temperature [2], hot pressing [3], pressureless sintering, infiltration [4, 5, 6, 7], squeeze casting and shock wave consolidation. The major challenge in any process to produce diamond composites is to produce a thin, clean, strong interface between the diamond and the metal. Most metals (except carbide formers) have poor wetting with diamond and form weak or no bonds. Hence, it might be necessary to use carbide formers to form these interfaces for wetting and bonding. The interface is especially important for the thermal cycling and long term reliability of the semiconductor device. Copper has poor wetting with diamond and it is difficult to produce a good bond between the matrix and the diamond in the copper-diamond metal matrix composites (CDMMCs). However, this problem can be overcome by using accordance with ISO 3369. The surface roughness was measured using a TK100 surface analyzer in accordance with copper alloys with elements which have affinity for carbon. The present work explores the possibility of using copper alloys with elements which have affinity to diamond for producing CDMMCs using gas pressure assisted infiltration technique. Furthermore, the thermo-physical properties of the copper-diamond composites are evaluated and related to the composite microstructure.

2. Experimental and Results

The copper-diamond composites were produced by gas pressure assisted infiltration of copper alloys with high conductivity diamond particles. The diamond powders (commercially available) had a mesh size of 70-80. The quality and volume content of the diamond has a strong effect on the final thermal conductivity of the composite. The hydrogen, oxygen, and nitrogen content were <4 ppm, <210 ppm, and <250 ppm respectively. The copper alloys investigated in this study were a custom Cu-Si with chrome additions (A) and a commercially available Cu-Si (B). The diamond particles were filled in the graphite molds to a desired final composition. The filled molds were sealed and evacuated to a vacuum to remove trapped air in the mold. The mold was heated in a vacuum furnace at 10°C/min to above the melting temperature of the alloy and held at this temperature for 15 min before applying a gas pressure. After infiltration the mold is furnace cooled while holding the pressure. The infiltrated specimens are shown in Figure 1.

The samples were characterized for density, surface roughness, λ, CTE. The sample densities were measured using the standard Archimedes density principle in DIN 4777. CTE was measured with a Netzsch model 402 C push rod

dilatometer. The samples were tested in a dynamic helium atmosphere (gas flow rate: 50 ml/min) between 10 and 160°C at a heating rate of 3 K/min. Further on, the reproducibility was checked by measuring the same sample twice. The thermal diffusivity and specific heat were measured using a Netzsch model LFA 447 *Nanoflash*™ diffusivity apparatus. For this, the system was calibrated with an aluminum standard prior to the sample test run.

Fig. 1. Gas Pressure Infiltrated copper-diamond composite specimens, on the left are A and on the right B diamond composites.

The measured data was used to calculate the thermal conductivity according to the following equation:

$$\lambda = \rho \cdot c_p \cdot \alpha \, . \qquad (1)$$

where λ is the thermal conductivity, ρ is the density, c_p is the specific heat and α is the thermal diffusivity.

The infiltrated samples had near full density (>99% theoretical). The surface roughness values of diamond composites show a reasonably good surface quality (Ra ~4-6 μm). The thermal conductivity and coefficient of thermal expansion are shown in Fig. 2. The thermal conductivity of A diamond composite is around 600 W/m.K and that of B diamond composite is around 160 W/m.K. This difference can be explained by considering the λ of the starting matrix. In commercially available B a high silicon content siginificantly reduces the thermal conducitivity of the copper alloy to about 40-50 W/m.K leading to an overall low conductivity for the composite.

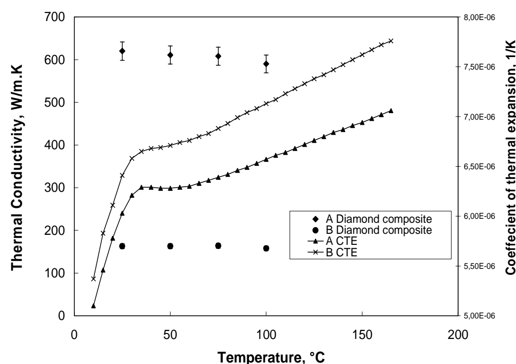

Fig. 2. Thermal conductivity and coefficient of thermal expansion of diamond composites.

The CTEs for copper and diamond are 16.5-17×10^{-6} K^{-1} (20-300°C) and 1.5-4.8×10^{-6} K^{-1} (127-927°C), respectively. Therefore, it is expected that the CTE of the composite will be lowered with addition of diamond particles. The measured CTE for A diamond and B diamond are shown in Figure 2. The CTE for A diamond composite is 5.1-7.06×10^{-6} K^{-1} (20-160°C) and for B diamond composite it is 5.37-7.76×10^{-6} K^{-1} (20-160°C), which is in the range of the currently used InP and GaAs semiconductors. With higher diamond contents the CTE can be further reduced in the operating range of silicon chips, with a concomitant increase in λ and hence an overall better thermal performance.

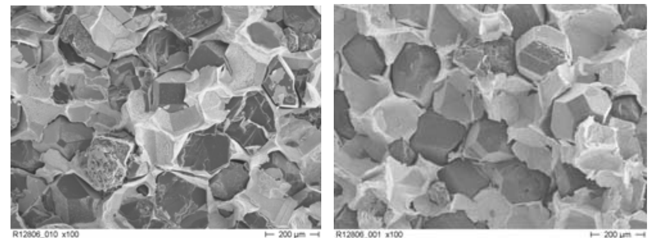

Fig. 3. Fracture surfaces of A (left) and B (right) diamond composites.

The fracture surfaces of the A and B diamond composites are shown in Fig. 3. There is no evidence of porosity between the diamond surface and the matrix. The fracture modes with no evidence of diamond particle pull out indicating good interfacial bonding.

3. Summary

High λ and tailored CTE (4-7 ppm/K) copper-diamond composites can be manufactured with relative ease and economically, using gas pressure infiltration technique. The alloying additions need to be sufficient enough to form an optimum amount of interfacial layer for thermal transfer across the interface. In future, silicon content will be optimized for higher λ in the diamond composites.

4. References

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