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Dymalloy: A Composite Substrate for High Power Density Electronic Components

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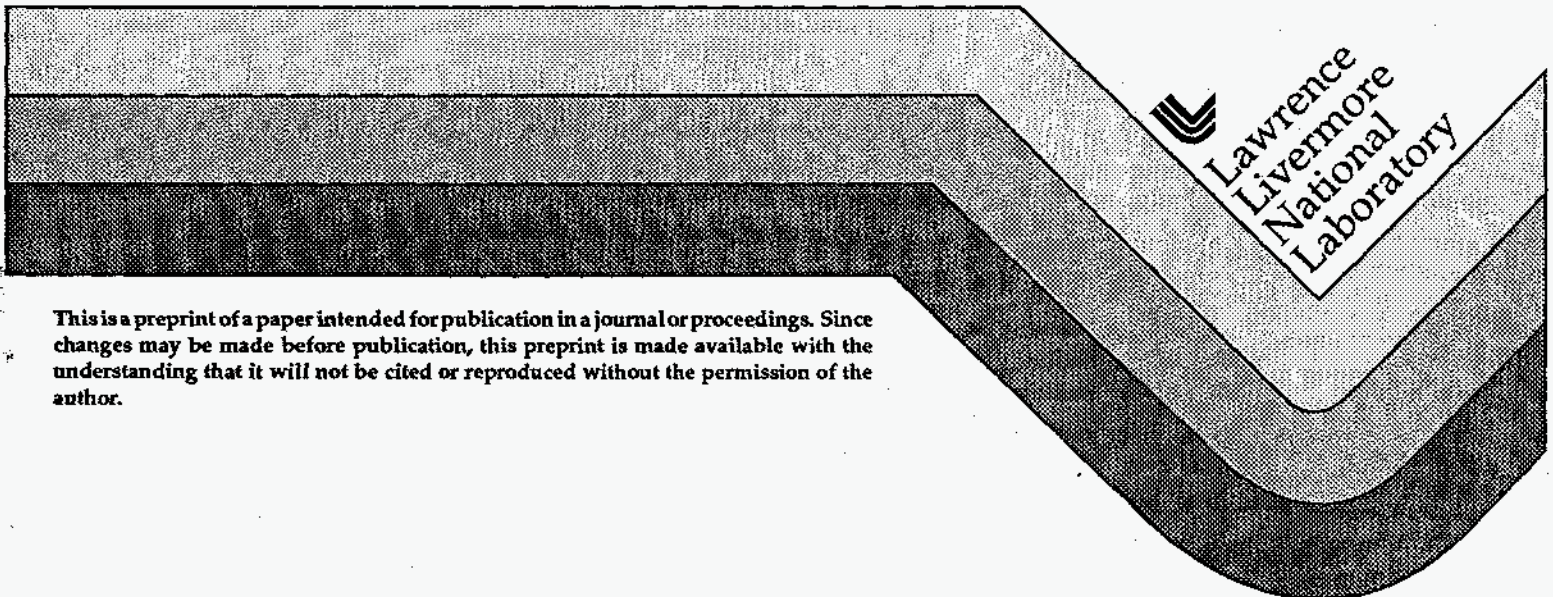
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Dymalloy

A Composite Substrate for High Power Density Electronic Components

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Abstract

High power density electronic components such as fast microprocessors and power semiconductors must operate below the maximum rated device junction temperature to ensure reliability. Junction temperatures are determined by the amount of heat generated and the thermal resistance from junction to the ambient thermal environment. Two of the largest contributions to this thermal resistance are the die attach interface and the package base. A decrease in these resistances can allow increased component packing density in MCMs, reduction of heat sink volume in tightly packed systems, enable the use of higher performance circuit components, and improve reliability.

The substrate for high power density devices is the primary thermal link between the junctions and the heat sink. Present high power multichip modules and single chip packages use substrate materials such as silicon nitride or copper tungsten that have thermal conductivity in the range of 200 W/mK. We have developed Dymalloy, a copper-diamond composite, that has a thermal conductivity of 420 W/mK and an adjustable coefficient of thermal expansion, nominally 5.5 ppm/C at 25 C, compatible with silicon and gallium arsenide. Because of the matched coefficient of thermal expansion it is possible to use low thermal resistance hard die attach methods.

Dymalloy is a composite material made using micron size Type I diamond powder that has a published thermal conductivity of 600 to 1000 W/mK in a metal matrix that has a thermal conductivity of 350 W/mK. The region of chemical bonding between the matrix material and diamond is limited to approximately 100 Å to maintain a high effective thermal conductivity for the composite. The material may be fabricated in near net shapes.

Besides having exceptional thermal properties, the mechanical properties of this material also make it an attractive candidate as an electronic component substrate material.

Key words: substrate, package base, composite material, diamond composite

Introduction

Modern microprocessors have reached power densities of 77 W/cm² [1], and are

predicted to rise to 200 W/cm² [2]. Power semiconductors, such as the die in a 350 W BUS50 TO-3 power transistor, may operate at a power density of 660 W/cm² [3]. To ensure

correct operation and adequate life it is necessary to limit the junction temperature to less than 200 C for discrete power semiconductors, 125 C for military logic devices, and as low as 70 C for some commercial logic devices. For many high power density devices much of the allowable temperature budget is expended in the package base and die attach thermal resistances.

The ideal material for a package base would have infinite thermal conductivity and a CTE perfectly matched to the semiconductor material. The need for high thermal conductivity is obvious. The good CTE match is required because thermally induced shear stress at the die bond is directly proportional to the mismatch in CTE and the length from the center of the die to a corner.

The best thermal conductivity available in a naturally occurring material is about 2200 W/mK for good quality Type IIa diamond. Pure copper has a thermal conductivity of 393 W/mK. Common package base materials such as copper-tungsten, AlN, and BeO all have thermal conductivities near 200 W/mK. The new aluminum silicon carbide composites also fall in this range. Copper diamond composite material, called Dymalloy, made with 55 vol% of good quality Type I diamond has a thermal conductivity of 420 W/mK.

While Type IIa diamond has been successfully employed as a heat spreader for laser diodes and some microwave devices, its CTE of 1.7 ppm/C, compared to 5.8 ppm/C for GaAs, limits its use with hard, high thermal conductivity, die attach methods to die generally less than 1 mm on a side. Dymalloy, made with 55 vol% diamond, has a perfect CTE match to gallium arsenide. Note that slightly increasing the diamond volume fraction allows the CTE to be adjusted to provide a perfect match to silicon. Values of the thermal conductivity and CTE of common semiconductor and substrate materials are shown in Table 1.

As an example consider a die with a power density of 100 W/cm² attached to a substrate with a 65 μm bond line. Using a silver-filled epoxy die attach will result in a temperature rise of 29C. Using a Au-Sn bond would result in a rise of 0.8 C. This is smaller than the 4.4 C rise through a typical 625 μm thick silicon die under these conditions. For extremely high power density conditions combining

thinned die with an activated nitride bond process [4] that can produce a bond line only 2000 Å thick may be appropriate.

Table 1. Properties of Common Semiconductor and Substrate Materials.

	Thermal Conductivity W/mK	CTE ppm/C
Si	150	4.2
GaAs	50	5.8
Dymalloy	420	5.5
Copper	393	17
Cu-W 25/75	230	8.3
BeO	210	6.7
AlN	180	4.5

Modern microprocessor die are often larger than 1.5 cm on a side. They are most often attached to their packages with a polymer die attach to provide a compliant joint that can absorb the shear stress caused by the difference in CTE between silicon at 4.2 ppm/C and copper tungsten at 8.3 ppm/C. A good silver-filled epoxy die attach material has a thermal conductivity of 1.9 W/mK. The thermal conductivity of Au-Sn 80/20 die attach alloy is 68 W/mK. For the same power density and thickness the silver-filled epoxy will have 36 times the temperature rise of the Au-Sn. Values for the thermal conductivity of some common die attach materials are shown in Table 2.

Table 2. Thermal conductivity of Common Die Attach Materials.

	Thermal Conductivity W/mK
Au-Sn 80/20	68
Au-Ge 88/12	88
Au-Si 97/3	27
Silver Glass	17
Silver-Filled Epoxy	1.9

Given that the total temperature rise budget from junction to ambient is only 60 C in the case of workstations, having a substrate that is CTE matched to the semiconductor provides a major advantage. Using a substrate with more than twice the thermal conductivity of any other CTE matched material provides additional margin.

Fabrication Considerations

The fabrication process for Dymalloy, a high thermal conductivity diamond-metal composite, was developed to address both technical and commercial requirements. The technical challenge is to combine diamond powders with a metal to produce a composite with high thermal conductivity. The commercial requirements are to produce this composite in near net shape and to be cost competitive with existing products. These two basic requirements have guided the development of Dymalloy.

In order to be cost competitive the diamond powder and metal matrix material must be readily available and both must have high thermal conductivity. The ideal diamond powder material would be free from defects and contaminants. These requirements are approached by Type IIa diamonds that have a typical thermal conductivity of 2200 W/mK. Type IIa diamonds are used for jewelry and are unavailable in powder form. CVD diamond films are the next choice for the composite with a thermal conductivity of 1400 W/mK. These films could be crushed into powders for the composite but this process is not economically feasible. The more common Type I diamond is commercially available as powder and is used for manufacturing operations such as grinding and lapping. Type I diamond has a measured thermal conductivity of 600 to 1000 W/mK and costs between \$0.50 and \$1.00 a carat. Type I diamond powder is used to make Dymalloy because of its availability and cost.

The reported thermal conductivity of diamond was measured on relatively large diamond samples and not on the diamond powder used for the composite. The bulk thermal conductivity of a material is size independent until the dimensions of the material approach the mean free path of the heat transport mechanism, electrons for metals and phonons for non-metals. The minimum size diamond powder used in the composite was estimated to be at least ten times the phonon mean free path in the diamond or approximately 1 μ . Graebner et.al. [5] showed that diamond grain size affects the thermal conductivity of CVD diamond films. As the grainsize increases the thermal conductivity increases until the grains are larger than approximately 20 μ . Dymalloy has been made with diamond powders in the 6 to 50 μ size range.

The variation in Type I diamond thermal conductivity is also a function of purity and internal defects. Diamond powders may contain a variety of metal impurities and a variable amount of nitrogen. Some diamond powders are manufactured to have a high density of internal defects.

For our application Type I diamond powder material should be selected to optimize the thermal characteristics of the composite. Dymalloy was made using diamond powders purchased from several vendors in order to optimize the composite properties.

Obtaining a high thermal conductivity diamond composite substrate requires that the diamond be chemically bonded to the matrix material. At the bond line between the metal matrix and diamond the metal electron thermal conductivity is converted into phonon conductivity. There is some evidence that the bonding material can affect this transition [6]. This is critical because the metal-carbon bond, or carbide, has relatively poor thermal conductivity. To minimize this effect the total thickness of this bond must be minimized. Materials such as titanium, tungsten, chrome, and zirconium have been used to form the carbide bond in Dymalloy. The majority of Dymalloy composites have been made using Tungsten - 26 % Rhenium as the bond material. Quantitative measurements of the effect of various bond material have not been made so the choice of using W-Rh is qualitative, based on observations during the fabrication process.

Fabrication of Dymalloy

The first step in the fabrication process is coating the diamond powder using a physical vapor deposition technique. To ensure uniform coating of the irregular diamond grains the powder is tumbled in the coating system. This is accomplished by placing the powder in a small metal pan that is mechanically vibrated in the vertical direction by a piezo-ceramic transducer. The diamond is coated in this system with approximately 100 Å of W-Rh. We have verified this thickness using TEM analysis.

All of the carbide forming materials oxidize in air and bonding to oxide surfaces is difficult. This problem is prevented by coating 1000 Å of a brazeable material, such as pure copper, on top of the carbide former in situ. The result is coated diamond powder that has 100 Å

of a carbide forming material overcoated with 1000 Å of brazeable material.

At this point the coated diamond powder can be packed into a form and vacuum infiltrated with the metal matrix material to form a composite. Although composites have been made using this technique, the diamond powder with these very thin coatings are difficult to form into a final shape before infiltrating. Control samples made using commercially available copper coated diamond powder were not as difficult to form. The commercial coated diamond powder has a thicker copper coating, several microns thick, that flows during the forming process. Although the commercial powder is easier to form, examination of this powder shows that the diamond grains are entrapped, not bonded, in the copper. An electroless plating process is used to increase the copper thickness to several microns on the coated diamond powder used in making Dymalloy. This added step makes the forming process easier.

The composite is made by placing the powder into a form, pressing the powder to the desired thickness, and infiltrating with the matrix material. This forming process was developed using commercially available copper coated diamond powder. The data from this development is directly applicable to making Dymalloy. Experiments were made to determine the initial filling thickness of diamond powder, the pressure necessary to compact the form, and the amount of metal matrix material that is needed for the infiltration process so that the final composite meets thickness and dimensional tolerances.

The final step is infiltrating the formed diamond powder with a high thermal conductivity material. We presently use a copper-silver (20/80) alloy that has a thermal conductivity of 354 W/mK and a melting point of approximately 800 C. Other materials such as copper with a thermal conductivity of 393 W/mK can be used, but the lower melting temperature alloy avoids problems with graphitization of the diamond.

The infiltration process is done in a vacuum and capillary action allows the metal braze to wick into the preform. Using an amount of braze material just sufficient to thoroughly wet the preform ensures that the composite does not deform upon cooling due to the differences in the coefficient of thermal expansion between

the braze material and the composite. Other manufacturing processes that combine sections of these last two steps can be envisioned but have not tried.

Material Properties

The material properties that have been measured include density, porosity, diamond fraction, specific heat, coefficient of thermal expansion, thermal conductivity, speed of sound, and the mechanical stress - strain relation. Some of the properties such as density, specific heat, and the coefficient of thermal expansion can be determined from a rule of mixtures formula assuming the volume fraction of diamond in the composite and are verified by measurements. These estimates also assume that the composite is fully dense.

The diamond volume fraction is determined by measuring the porosity and density. We determined that the composite was fully dense by using mercury porosimetry technique. Any porosity would have a detrimental affect on the thermal conductivity of the composite. The measured density of 6.4 g/cc was then used to determine the diamond volume fraction of 55%.

Both the specific heat and the coefficient of thermal expansion for several test pieces were measured as functions of temperature. The average specific heat for temperatures between 25 and 75 C was measured to be $0.316 + 8.372 \times 10^{-4} T$ (J/gK). The average CTE between 25 and 200 C was $5.48 + 6.5 \times 10^{-3} T$ (ppm/C).

The thermal conductivity of a composite material is a combination of the thermal conductivities of the constituents. The thermal circuit through the composite is made up of many parallel and series conduction paths. A simple unit cell estimate of the effective thermal conductivity of the composite, assuming the diamond at 1000 W/mK and the matrix at 400 W/mK gives 660 W/mK. Bounds on the effective thermal conductivity of the composite can be made using the formula given in [7]. Figure 1 shows the bounds of the effective thermal conductivity for the composite as a function of diamond thermal conductivity.

Bounding values of the effective thermal conductivity for the composite as a function of matrix material thermal conductivity is shown in Figure 2. In this plot the diamond

thermal conductivity is 1000 W/mK and the diamond loading is 55 vol%. As the matrix thermal conductivity decreases the difference between the upper and lower bound increases. Estimates of the effective thermal conductivity of a diamond composite correspond to the lower bound values. The measured thermal conductivities of epoxy-silver and epoxy-diamond composites also agree with lower bound estimates.

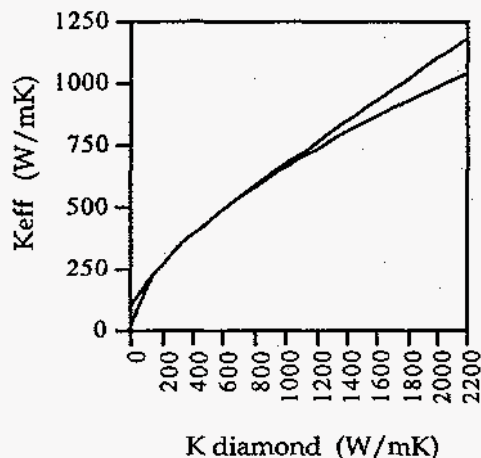


Figure 1. Bounds of the effective thermal conductivity if the composite as a function of diamond thermal conductivity. The matrix thermal conductivity is 354 W/mK and the volume fraction of diamond is 55%.

The speed of sound and the stress-strain relation are difficult to estimate but they were measured. Ultrasound techniques were used to measure the speed of sound at 7000 m/s in the copper diamond matrix material. This sound speed is comparable to aluminum, molybdenum, titanium, tungsten carbide, and calcium fluoride. The stress strain relation for Dymalloy shows that the material does have some plastic characteristics. Dymalloy has a linear stress-strain relation for stresses up to 40 kpsi and strains of approximately 0.1 to 0.2 %. After this linear region the stress increases and failure occurs between 50 and 60 kpsi at strains of approximately 5.0 to 6.0 %. Examination of the fractured surfaces, shown in the magnified portion of Figure 3, shows that brittle fracture occurs in the diamonds and the matrix fails in a ductile manner. The stress-strain relation shows that Dymalloy is not a brittle material but has

some plastic characteristics which could prove to be advantageous for manufacturing purposes.

Because Dymalloy is fabricated using a powder process it is straightforward to process components to near-net shape. The as fabricated surface has some texture from the embedded diamond particles. If a smoother surface is required it is possible to plate up the surface and polish it.

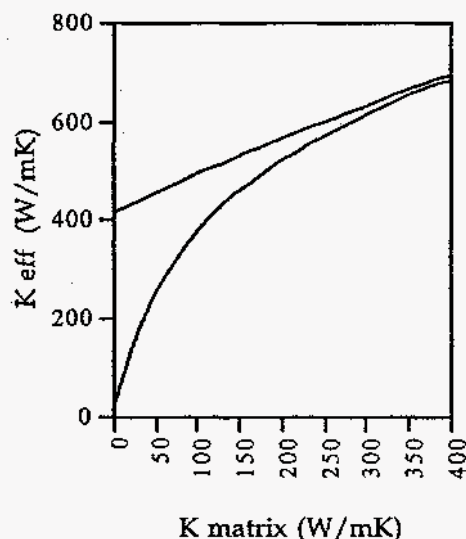


Figure 2. Effective thermal conductivity of a diamond composite as a function of matrix material thermal conductivity. The diamond thermal conductivity is 1000 W/mK and the loading is 55vol%.

Conclusion

Dymalloy has been developed as a substrate material for use in high power density packaging. The principle advantages of this material are that it has a thermal conductivity approximately twice that of present substrate materials and has a coefficient of thermal expansion that matches gallium arsenide and is adjustable to match silicon. Matching the CTE between the electronic component and the package base allows the use of hard die bond materials that have relatively high thermal conductivities. This reduces the thermal resistance from the junction to case and enables the component to run cooler or at higher power.

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Figure 2. The figure shows two magnified views of the fracture surface of a Dymalloy disc. The lower magnification picture shows the uniform distribution of diamond in the metal matrix. The higher magnification photo at the bottom of the figure reveals high strength cleavage failure in the diamond particles.

