Challenges in Matching Die to Package CTE's for High Thermal Flux Devices

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INTRODUCTION

High heat flux devices such as lasers, high brightness LEDs, RF power transistors and power switching devices all require packaging which has high thermal conductivity in order to maintain useful operation of the device. Copper and water cooled copper are common package configurations with good thermal characteristics but copper's high CTE makes it a poor CTE match to most semiconductor materials. The use of diamond as a thermal heat spreader is well known in the industry but diamond's low CTE diminishes its use where robust hard solder die attach is required. Several materials including composites have been developed which have better CTE matching characteristics but most do not have the high thermal conductivity of either copper or diamond and may have other restrictions which limit widespread usage. The ideal material would have variable CTE matching, copper level or higher thermal conductivity, a choice of conductive or insulating die attach surfaces, precise edges and no compositional variability from point to point in the material.

DISCUSSION

Figure 1 shows the thermal conductivity (the red columns) and the coefficient of thermal expansion (the open triangles) for ten traditional heat spreader materials. To remove heat effectively from a laser diode array, the heat spreader should have thermal conductivity at least as high as that of copper (400 watts / meter / K). The only traditional heat spreader materials which meet that criterion are copper and diamond, both of which have severe CTE mismatches with a GaAs laser array.

To solve this problem, various manufacturers have developed heat spreaders made from metal-diamond composite materials, such as copper-diamond or silver-diamond. For example, Plansee offers heat spreaders made from a silver alloy reinforced with diamond particles. The thermal conductivity of these heat spreaders can exceed 550 watts / meter / K. CTE can be tuned over the range from 5.0 to 8.0 ppm / K by adjusting the volume fraction and the grade of the diamond powder. Unfortunately, these metal-diamond composite heat spreaders perform inadequately in many applications because of the poor quality of their edges, surfaces, and internal morphology.

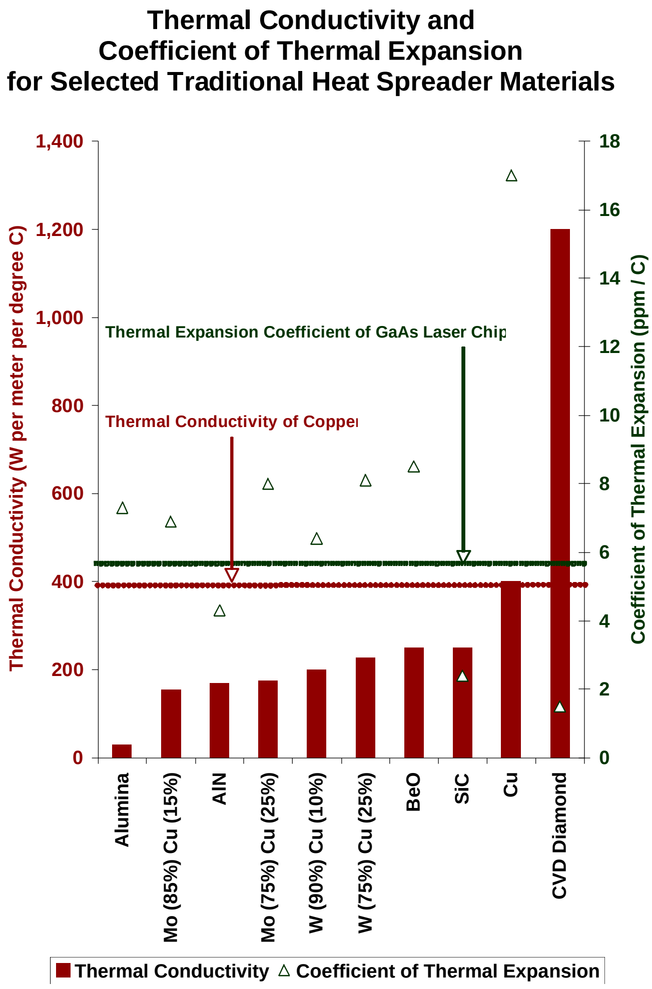

Figure 1

- *Poor edge quality.*

  In some applications, the heat spreader must have a high-quality edge. A high-quality edge enables the heat spreader to meet two geometrical requirements: 1) the heat spreader must extend all the way to the periphery of the laser diode array, but 2) it must not block any photons in the beam of the edge-emitting laser. Unfortunately, the manufacturers cannot reliably mold the composite material to a high-quality edge. Having molded the composite material, they cannot machine a sharp edge because of the rough surface and the difference in lapping rates between metal and diamond.

- *Poor surface quality.*

  Metal-diamond composite heat spreaders also have difficulty meeting specifications for surface roughness. The manufacturers create these structures by mixing diamond grit with molten silver or copper. One approach is to mix the diamond grit into a vat of molten metal; another approach is to form a matrix of diamond grit and then infiltrate the matrix with molten metal. In either case, when the composite cools, the metal shrinks more than the diamond. As a result, the surface of the composite becomes rough with diamond bumps over very short distances. It is difficult to polish the surface mechanically because diamond and Cu have different lapping rates.

  The manufacturers can ameliorate this roughness problem by using smaller diamond particles, but smaller diamond particles reduce the thermal conductivity of the composite. It would be possible to improve the surface roughness by plating copper over the composite, but this additional plating step increases manufacturing costs, reduces the thermal conductivity of the composite, and complicates the problem of CTE matching.

- *Poor internal morphological quality.*

  The internal morphology of the composite materials determines its physical properties. If the morphology varies from point to point, so does the thermal performance of the material. Manufacturers who mix diamond grit into a vat of molten metal have to accept the fact that the diamond particles tend to rise to the surface because they're less dense than the metal. Manufacturers who constrain the diamond particles in a matrix and then infiltrate the matrix with molten metal have to make sure they wet the entire surface of the diamond; otherwise, they can leave voids in the composite. Both of these problems can lead to inhomogeneous material with local variations in thermal conductivity and CTE. These local variations in thermal conductivity and CTE of the heat spreader can degrade the performance characteristics and the operating lifetimes of the lasers.

  From a more rigorous perspective, the microstructure of the composite material is inherently inhomogeneous. Even if the manufacturers could create a non-porous material with evenly distributed particles, the material would remain a heterogeneous mixture of diamond grit mixed in metal. The thermal conductivity and CTE specifications which the suppliers advertise can only be average values. At one point on the device, the surface may be pure copper, while 100 microns away, a large diamond particle may lie on the surface. The local properties of the composite material in these two regions will differ substantially. As a result, the thermal environments of two adjacent devices will also vary.

- *Solutions*

The solution to these problems is to create a laminated structure with layers of copper and diamond separated by a filler metal, as shown in Figure 2. To fabricate these devices, high-strength bonding techniques which are used to bond diamond onto tungsten carbide for cutting tools can be used with equal effect to bond the two diamond layers to each other. Subsequent application of the outer metal layers yields a five layer structure where the CTE of the outer two surfaces is determined by the thicknesses of the various layers as shown in the equation below.

Diamond-Copper Laminate Heat Spreader

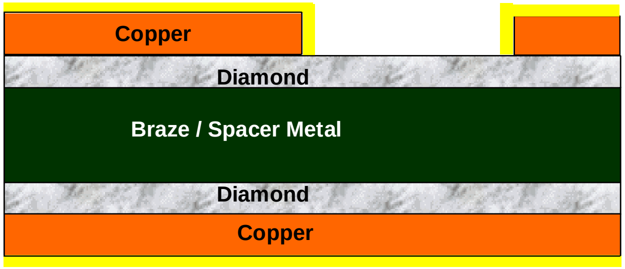

Figure 2

$$t_D = \left[t_{M1} \times \left(\frac{E_D}{E_{M1}} \right) \times \left(\frac{CTE_{M1} - CTE_C}{CTE_C - CTE_D} \right) \right] + \left[t_{M2} \times \left(\frac{E_D}{E_{M2}} \right) \times \left(\frac{CTE_{M2} - CTE_C}{CTE_C - CTE_D} \right) \right]$$

- t_D = thickness of the first and second diamond layers
- t_{M1} = thickness of first outer metal layer
- t_{M2} = thickness of second outer metal layer
- E_D = Young's modulus of the first and second diamond layers
- E_{M1} = Young's modulus of first outer metal layer
- E_{M2} = Young's modulus of second outer metal layer
- CTE_D = coefficient of thermal expansion of the first and second diamond layers
- CTE_{M1} = coefficient of thermal expansion of first outer metal layer
- CTE_{M2} = coefficient of thermal expansion of second outer metal layer
- **CTE_C = coefficient of thermal expansion for surface of multilayered structure**

The thickness of the inner metal layer normally equals the sum of the thicknesses of the two outer metal layers.

Prototypes of these laminated diamond-copper heat spreaders have been fabricated and then interposed between laser diode arrays and copper packages using standard gold/tin solder. Subsequent analysis and testing yielded the following results.

RESULTS

- *High thermal conductivity, equal to or greater than that of copper.*

  Figure 3 shows measured data indicating that prototypes of diamond-copper laminate heat spreaders cool laser diode arrays as effectively as copper heat spreaders. Direct measurement of the lateral and vertical thermal conductivity resulted in values between 350 and 400 W/meter-K.

- *CTE matching with the host material.*

  The CTE of a diamond-copper laminate heat spreader can have any value between the CTE of diamond and that of copper (1.5 to 17 ppm / K). The CTE depends on the relative thicknesses of the copper and diamond layers. Customer data from testing of a prototype diamond-copper laminate heat spreader with an 8 mm laser diode array and copper package attached showed that the assembly passed all thermal cycling tests according to Telcordia specifications. The results confirm that the CTE of the diamond-copper laminate heat spreader matched that of the laser diode array.

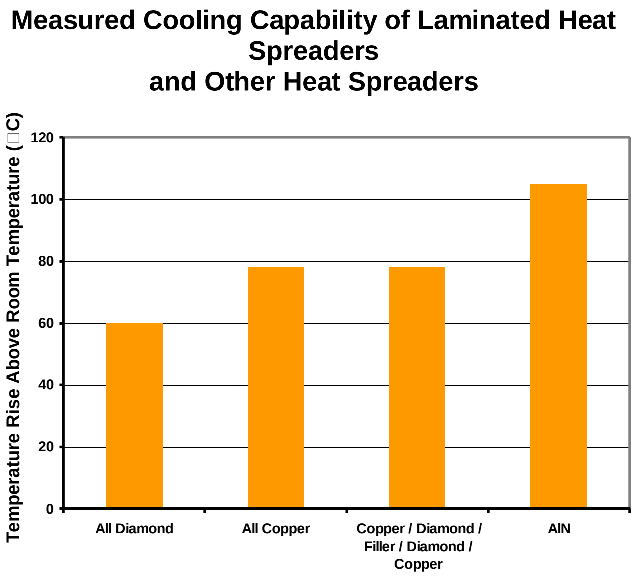

Figure 3

- *Excellent surface quality.*

  Standard deposition techniques allow precise surface roughness control on both mounting surfaces. Surface roughness equal to 0.1 micron peak-to-valley has been measured on diamond-copper laminate heat spreaders.

- *Excellent internal morphology quality.*

  The material is fully dense. The local thermal conductivity is the same at every point where the laser diode array touches the heat spreader.

- *Precise edge control.*

  The use of discrete continuous layers allows the use of traditional patterning and etching of the various layers. In some cases self aligned etching of the diamond layer can be used to create zero set back metal edges which can substantially improve the output of the laser and the overall thermal performance.

- *Controllable electrical properties.*

  The use of continuous diamond layers in the structure allow the heat spreader to be either electrically conductive (by doping the diamond with boron) or electrically insulating, depending on the requirements of the application. High voltage isolation is easily achieved with the insulating films and stable ground planes can be made using conductive films. In both cases, thicknesses down to 100 microns minimize the overall thermal resistance in the package assembly. Heat spreaders made by the competing technical approaches don’t offer this versatility; AlN heat spreaders are electrically insulating and CuW and diamond-Cu composites are electrically conductive but neither can be made thin enough to measurably reduce thermal resistance. Patterning and etching of the insulating diamond also allows selected portions of the top metal layer to contact the inner and bottom layers to create vias without laser drilling.

CONCLUSIONS

Diamond/copper laminate heat spreaders offer a complete solution to both CTE matching and thermal control for high power semiconductor packaging. Reliable hard solder die attach techniques can be used to bond large high CTE compound semiconductor dice directly to copper packaging without compromising either reliability or thermal performance. Consistent structural morphology allows traditional patterning to be used to create low setback metal at the edges and the laminate approach insures uniform point to point thermal conductivity. In addition, the high dielectric strength of the diamond makes high voltage isolation feasible without increasing thermal resistance in the package assembly.