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# CVD DIAMOND FOR MICROELECTRONIC AND OPTOELECTRONIC THERMAL MANAGEMENT APPLICATIONS

## ABSTRACT

CVD diamond (synthetic diamond made by a chemical vapor deposition process) is an important family of materials used in microelectronic and optoelectronic packaging and for laser and detector windows. Its ultra-high thermal conductivity (up to 200 W/m-K) enables increases in microprocessor frequency and output power of microelectronic and optoelectronic devices. This paper presents an overview of manufacturing processes, properties, cost and applications.

## INTRODUCTION

The ability to dissipate heat limits output levels of many high-power microelectronic and optoelectronic applications, such as radar and other radio-frequency (RF) devices, power semiconductors, laser diodes and light-emitting diodes (LEDs). It also controls frequency of microprocessor units (MPUs). In addition, thermal management affects device performance and reliability. Evidence of the criticality of heat flux in MPUs is the acknowledgement by Intel that it had run into a "thermal wall" [1]. In a practical example of the seriousness of thermal management, a laptop user suffered burns requiring medical treatment [2].

In response to the need for improved heat dissipation, various forms of liquid cooling and refrigeration are being considered. For example, the Apple Power Mac G5 has a pumped liquid cooling system very similar to those used in automobiles. It includes a pump, heat exchanger (radiator), radiator fan, and uses a water-propylene glycol working fluid. All liquid cooling systems have significant drawbacks, including parts and labor costs, reduced reliability and increased weight. Several websites report Power Mac G5 heat transfer fluid leaks in service [3]. In addition, the fluid pump consumes power. Use of materials with extremely high thermal conductivities can extend the use of convection cooling, potentially overcoming the need for liquid cooling.

Thermoelectric coolers (TECs), which require power input, are widely used for temperature control of laser diodes and micromechanical devices. Materials with high thermal conductivities can improve TEC efficiency, reducing power consumption.

The thermal management problem places a premium on materials with high thermal conductivities. Some forms of diamond have thermal conductivities that are higher than that of any other thermal management material. In particular, polycrystalline diamond made by chemical vapor deposition (CVD) can have room temperature thermal conductivities as high as 2200 W/m-K, making it an attractive candidate for applications with high heat fluxes [4].

In addition to technical thermal problems, cooling costs have become a major issue. Energy rates are a significant and increasing factor in total cost of ownership (TCO) [5]. Power consumed in cooling electronic and photonic systems by TECs and liquid cooling systems have direct costs, and place an additional burden on building cooling costs. More efficient thermal materials have the potential to reduce TCO.

## CVD DIAMOND PROCESSES AND PRODUCTS

Diamond, as a material, is known for its wide range of extreme properties. It offers ultra-high thermal conductivity, transparency across a variety of wavelengths, and is wear resistant, electrically insulating and chemically inert. Man-made polycrystalline CVD diamond films offer all of the outstanding characteristics of single crystal diamond without the size and shape limitations of natural diamond. CVD diamond is a family of materials with process-dependent properties. Polycrystalline diamond via a CVD process is grown on substrates, typically refractory metal or Si, although other substrate materials can be used. This highly engineered material can be produced as flat plates or thin-walled three-dimensional structures, such as hemispheres and paraboloids. Diamond plates can be made by a variety of CVD processes, including hot filament, microwave plasma, DC plasma, plasma jet, arc discharge, laminar oxy-acetylene flame, and turbulent oxy-acetylene combustion [6].

The diamond growth can be tailored to the specific application, which results in a range of products from tool-grade material with high fracture toughness to high clarity optical window material suitable for FTIR spectroscopy. Adjustments in growth conditions produce parts with thickness varying from about a half a micron to over a millimeter. Heat spreader parts typically range in thickness from 100 microns to 500 microns. Diamond heat spreader parts can be matched to the thermal needs of the customer, enabling diamonds with thermal conductivities ranging from 500 to 2100 w/m-K thru plane.

After growth to the required thickness, the substrate is often removed, creating a free standing diamond part. Several post-processing steps are available to further customize the part to the application. When bonding the diamond to other materials a smooth surface is required. While the unpolished roughness of the growth side of the diamond starts at around 10% of the diamond thickness, the peak-to-valley polished roughness can be reduced to about 10nm with a polishing step. Parts can be laser cut to the size and shape needs of the package of the end-user. Engineered laser systems and computer controlled motion allow specialized cutting of complex geometries, including microchannels, vias, scribing, etc.

Metallization is an important part of heat spreader preparation. While a standard scheme uses titanium for adhesion, platinum as a diffusion barrier and gold for bonding, other schemes are available. AuSn offers a low-temperature braze layer. The use of copper as a metallization scheme can reduce the impact of differences in coefficient of thermal expansion when using diamond with other materials. Packages including diamond with AlN, GaAs and SiC and Al/SiC have been introduced.

## PROPERTIES OF THERMAL MANAGEMENT AND LASER WINDOW MATERIALS

In recent years, there have been a number of new monolithic and composite materials developed to meet increasing microelectronic and optoelectronic heat dissipation issues [7-9]. Only one, highly-oriented pyrolytic graphite (HOPG), has a thermal conductivity approaching that of CVD diamond. Although some forms of HOPG have high in-plane thermal conductivities, through-thickness values are extremely low. All forms are electrically conductive.

CVD diamond is actually a family of materials, with a wide range of process-dependent properties. The material is somewhat anisotropic, with through-thickness thermal conductivities somewhat higher than inplane values.

Some forms of CVD diamond are optically transparent, making it an attractive material for applications requiring both this property and high thermal conductivity.

One of the key issues encountered in comparing properties of packaging materials is that values found in common sources, papers, book articles and manufacturer's data brochures, often vary greatly. For these cases, ranges are presented.

The thermal conductivity differences between that of CVD diamond and those of other packaging materials is particularly severe for electrically insulating materials. Table 1 presents properties of electrically non-conductive materials used in microelectronic and optoelectronic packaging. As discussed, CVD diamond is slightly anisotropic, and through-thickness values are presented.

Table 1 clearly shows the significant advantage of CVD diamond over other dielectric materials. This is particularly true when optical transparency is required, because materials like glasses, acrylics and zinc selenide have low thermal conductivities

Table 2 presents the properties of CVD diamond and electrically conducting materials used in microelectronic and thermoelectric packaging. Here, again, CVD diamond has a significant advantage over competing materials, except for HOPG, which, as discussed, is strongly anisotropic. Its through-thickness thermal conductivity is only about 25 W/m-K.

We note that the density of CVD diamond is much lower than that of most packaging materials, which is important in weight-critical applications, such as aircraft and

spacecraft electronic systems, notebook computers and other mobile devices. In addition, density is important even for stationary applications, because stresses arising from shock loads during shipping (50g is a common requirement) depend directly on component mass.

Another unique characteristic of CVD diamond is that some forms have extremely high elastic moduli, which range up 1050 GPa, compared to 70 for aluminum [10]. .It also is one of the hardest known materials.

Coefficient of thermal expansion (CTE), another important packaging material property, is discussed in the next section.

## DESIGN ISSUES

In addition to heat dissipation, thermal stresses arising from differences in coefficient of thermal expansion (CTE) is another critical packaging issue. The high CTEs of copper and aluminum can cause high thermal stresses when they are attached to the semiconductors and ceramics used in electronic and optoelectronic applications, which have CTEs in the range of about 2 to 7 ppm/K. A common approach to this problem is to use compliant solders, such as indium alloys, and polymeric thermal interface materials (TIMs), which include greases, gels, and phase-change materials, etc. However, polymeric TIMs have very high thermal impedances, and increasingly account for the bulk of the total thermal impedance. Another approach is to use compliant solders, which are typically indium based.

In one case, layers of pure aluminum, which has a low yield stress, were added to the top and bottom surfaces of a CVD diamond plate [11]

One solution to this problem is to use low-CTE materials for heat spreaders. These include CVD diamond, Kovar, copper/tungsten, copper/molybdenum, and the new composites and monolithic thermal management materials presented in Table 2.

The CTE of CVD diamond, 1.0-1.5 ppm/K, is lower than desired for some applications. This can be overcome by adding layers of copper on top and bottom, creating a laminate with a tailorable CTE [11]. The same principal is used for low-CTE laminated metal heat spreaders, such as copper-Invar-copper and copper-molybdenum-copper. However, as Table Another approach is to use CVD diamond encapsulated with low-CTE composite materials such as silicon-carbide particle-reinforced aluminum, commonly called AlSiC.

Size has a significant effect on thermal stresses. In general, thermal stresses increase linearly with planar dimensions (length and width). Consequently, CTE differences may not be significant when device dimensions are small. This issue can be addressed by analysis.

Finite element model (FEM) analyses are widely used in microelectronic and optoelectronic packaging. This applies to both temperature distributions and resulting thermal stresses. To minimize cost it is important not to over specify the requirement for thermal conductivity, planar dimensions, and thickness. For example, as discussed in the next section, the cost of CVD diamond increases with increasing thermal conductivity and dimensions. FEMs can establish thermal conductivity and dimension values that will meet requirements.

## COST ISSUES

Since diamond growth and post processing conditions can be altered to create parts with different thermal properties and cost, thermal modeling is an important step in the design stage to maximize the cost-value relationship of the CVD diamond part. In general, cost increases with plate planar dimensions, thickness and thermal conductivity. Thermal modeling often shows that the heat spreader required in diamond material is often thinner and has smaller inplane dimensions than heat spreaders made from traditional materials, which have much lower thermal conductivities. Optimizing the diamond heat spreader for each application has enabled more frequent use of diamond in high power packages

The reason that cost increases with thermal conductivity is that there is an inverse relationship between growth rate and thermal conductivity [12]. That is, it takes longer to make a heat spreader with high thermal conductivity, increasing manufacturing cost.

As discussed earlier, materials with high thermal conductivities have a variety of potential benefits that can contribute to reduced total cost of ownership, including: elimination of the need for liquid cooling; reduced system cooling power consumption; reduced building power consumption; and increased operational lifetime.

## APPLICATIONS

CVD diamond is used in a large number of microelectronic, optoelectronic and specialty applications, including: laser diode, laser crystal cooling, microwave device and power semiconductor heat spreaders, submounts and substrates [12-15 ]. In one case, it was an enabling material for reduction of the size of multi-chip power module packages [12], and flip chip packaging has increasingly incorporated diamond into the design.

The exceptional broad band infrared, terahertz and ultraviolet transparency of diamond combined with its low scatter make it highly applicable in optical applications. The unique combination of optical transparency and high thermal conductivity has led to use of CVD diamond in a variety of applications requiring these properties. For example, CVD diamond windows are used in short-wave UV, infrared, $CO_2$ laser exit windows and output couplers and high-power microwave devices [13]. The parts can be anti-reflection coated to further increase transparency. These windows can be supplied as free-standing parts or mounted to a flange.

The properties of diamond are increasingly being utilized in high energy research for both detection and imaging applications. As a detector material, diamond's key characteristics include beam resistance, fast response and low noise. The radiation resistance of CVD diamond has led to its use in particle physics detectors [13] and a millimeter-wave vacuum edge-cooled windows for electron cyclotron heating in thermonuclear plasma fusion energy research [4]. Diamond has also found use as lenses, monochrometers and beam splitters.

High-power military and space applications, challenged for size and weight, have found diamond to be a useful material. CVD diamond also has found its way into the designs of RF Power packages, amplifiers, radar devices and infrared cameras.

## SUMMARY AND CONCLUSIONS

CVD diamond is a family of materials that has unique combinations of properties, including ultra-high thermal conductivity, optical transparency and very high elastic modulus and hardness. This has led to increasing use in micromechanical, optomechanical heat spreaders, laser windows and other applications. Because material cost increases with increasing properties and material volume, it is important to define requirements carefully, using finite element models. As production volumes increase, cost will decrease, encouraging greater use of this important class of materials.

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| Material | Thermal Conductivity (W/m-K) | CTE (ppm/K) | Density ($g/cm^3$) |
|---|---|---|---|
| CVD Diamond | 500-2200 | 1.0-2.0 | 3.5 |

| Alumina (96%) | 20-35 | 6.0-7.1 | 3.7-3.9 |
|---|---|---|---|
| Aluminum Nitride | 60-250 | 3.5-5.7 | 3.2-3.3 |
| Beryllia | 254-275 | 5.9-9.0 | 2.9 |
| Quartz | 3 | 0.5-1.0 | 2.2 |
| Glass-Ceramics | 1.7-3.5 | 0.4-5.8 | 2.5-2.6 |
| Zinc Selenide | 16-18 | 7.6 | 5.3 |
| FR-4 PCB | 0.3 | 12-24 | 1.7 |

Table 1. Properties of selected electrically insulating materials used in microelectronic and optoelectronic packaging and laser windows.

| Material | Thermal Conductivity (W/m-K) | CTE (ppm/K) | Density ($g/cm^3$) |
|---|---|---|---|
| Copper | 400 | 17 | 8.9 |
| Aluminum | 218 | 23 | 2.7 |
| Kovar | 17 | 5.9 | 8.3 |
| Copper/tungsten | 157-190 | 5.7-8.3 | 15-17 |
| Copper/molybdenum | 184-197 | 7.0-7.1 | 9.9-10.0 |
| CVD diamond | 500-2200[1] | 1.0-1.5 | 3.5 |
| Carbon foam | 135-245[1] | -1 | 0.6-0.9 |
| HOPG | 1300-1700[2] | -1.0[2] | 2.3 |
| Natural graphite | 150-500[2] | - | - |
| Invar/silver | 153 | 6.5 | 8.8 |
| Continuous carbon fiber/aluminum | 218-290[2] | -1-+16[2] | 2.3-2.6 |
| Discontinuous carbon fiber/aluminum | 185[2] | 6.0[2] | 2.5 |
| Discontinuous carbon fiber/epoxy | 20-290[2] | 4-7[2] | 1.6-1.8 |
| Silicon/aluminum | 126-160 | 6.5-17 | 2.5-2.6 |
| SiC particle/aluminum (Al/SiC) | 170-220 | 6.2-16.2 | 2.8-3.0 |
| Beryllia particle/beryllium | 240 | 6.1 | 2.6 |
| Natural graphite/epoxy | 370[2] | -2.4[2] | 1.94 |
| Continuous carbon fiber/aluminum | 330[2] | -1[2] | 1.8 |
| Discontinuous carbon fiber/copper | 300[2] | 6.5-9[2].5 | 6.8 |
| Continuous carbon fiber/SiC | 370[2] | 2.5[2] | 2.2 |
| Continuous carbon fiber/copper | 400-420[2] | 0.5-16[2] | 5.3-8.2 |
| Continuous carbon fiber/carbon | 400[2] | -1.0[2] | 1.9 |
| Continuous carbon fiber/SiC | 370[2] | 2.5[2] | 2.2 |
| Diamond particle/aluminum | 550-600 | 7.0-7.5 | 3.1 |
| Diamond particle/copper | 600-1200 | 5.8 | 5.9 |
| Diamond particle/cobalt | >600 | 3.0 | 4.12 |
| Diamond particle/SiC | 600 | 1.8 | 3.3 |

Table 2. Thermal properties of CVD diamond and selected electrically conductive materials used in microelectronic and optoelectronic packaging.

1. Though-thickness
2. Inplane