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ABSTRACT

Diamond is the hardest and most wear resistant material known. It has a unique combination of the highest known thermal conductivity, and other properties which will make possible the creation of whole new families of products. These include optical windows, laser diode heat sinks, electronic thermal management substrates, radiation detectors, wear products, and cutting tools. Natural diamond is too expensive for most of these products, except in special applications. However, chemical vapor deposition (CVD) diamond technology is rapidly being developed as a method to cost effectively produce both diamond coatings and free-standing diamond parts for many new products. Many applications are already in commercial production, and are expanding rapidly. The vast potential for future CVD diamond applications is reviewed.

1. INTRODUCTION

Since the 1950's, synthetic single crystal and sintered polycrystalline diamonds have steadily increased their penetration of industrial markets. Synthetic diamond grits were first commercialized in the late 1950's, for use in cutting, grinding, and polishing of hard materials. Sintered polycrystalline tool and drill blanks appeared in the early 1970's. Synthetic diamond industrial consumption exceeded natural diamond consumption by 1970, and by the end of the 1980's it reached a value of roughly $500M worldwide. This growth in applications resulted from the exceptional properties of diamond (Table I) which made it the most cost effective material for many cutting and wear applications, and for small heat sinks and optical window applications.

Table I - Properties of CVD Diamond Compared to Other Materials

	CVD Diamond	Natural Diamond	Sintered Polycrystalline Diamond	Tungsten Carbide (6% Co)	Silicon Nitride	Silicon Carbide
Hardness (Knoop) (GPa)	85-100	50-100	50-75	18	16	20
Young's Modulus (GPa)	1180	1050	800	600	310	400
Thermal Conductivity (W/m°K)	600-1600 (in plane) >2000 (perpendicular)	1000-2000	500	100	40	135
Density (gm/cm^3)	3.51	3.51	4.1	15	3.2	3.2

The high pressure methods used to make synthetic diamonds have several major limitations. They require high temperatures and pressures, and the presence of a metal solvent or catalyst to accelerate the transformation of graphite to diamond during growth or sintering. These high temperatures and pressures require expensive equipment and controls and make the production of coated surfaces, curved shapes, and large pieces very difficult. The sintered products contain less than 100% diamond. The residual sintering aid and catalytic materials eliminate sintered high pressure diamonds from most electronic and optical applications.

New chemical vapor deposition (CVD) processes which overcome many of the limitations of the high pressure processes, have been under intense development since the late 1980's. In these CVD processes, diamond is deposited from a gas phase, and can therefore coat large areas and curved surfaces, or be grown thick enough to become free-standing parts which can be cut and finished to the size and shape desired.

The CVD processes typically include the maintenance of a plasma containing atomic hydrogen over the growth surface, and require a source of carbon such as methane (CH_4). Deposition chemistry research indicates that hydrogen is the key element which stabilizes the diamond surface, and permits the growth of diamond while suppressing the growth of graphitic carbon. The growth process typically requires temperatures of 800-1000°C, but can occur even at temperatures as low as a claimed 200°C (at much lower rates). Growth rates for different processes range from less than 1µ/hr. to over 100µ/hr. A variety of coated products, and products cut from free-standing diamond plates up to 2 mm or more thick are becoming available in significant volumes.

2. CUTTING AND WEAR APPLICATIONS

Diamond is the hardest material known, has a low coefficient of friction under most cutting environments (Table II), and has the highest thermal conductivity of any material. This combination of properties makes diamond the best material for many cutting, wear, and tribological applications.

Table II - Coefficient of Friction

Diamond Film	0.05 - 0.15
C2 Tungsten Carbide	0.17 - 0.46
Tool Steel (HRC = 62)	0.2 - 0.41
Teflon	0.05 - 0.1

There are some application areas where diamond is not suitable. For example, it is not suitable for the high speed cutting of materials which dissolve carbon or form carbides or for use in oxidizing atmospheres above 700°C.

However, diamond is superlative at cutting many extremely abrasive materials such as high silicon aluminum, carbon-carbon composites, SiC metal/matrix composites, honeycomb composites, and other emerging high performance aerospace materials.[1] The potential for diamond in cutting applications has generated a great deal of research and development activity, both within diamond film manufacturing companies, and in universities around the world.[2] Both thick film tools, made by brazing a thick free-standing piece of CVD diamond onto a supporting insert, and thin film coated tools are in production and are commercially available. End mills and round tools in both thick and thin film are successfully cutting and forming abrasive aerospace composites which cannot be machined with any other material.

Another application area which is rapidly emerging as a major market for CVD diamond is in wear protection. Seals, bearings, jet nozzles, micrometer tips, and other applications can take advantage of the anti-friction, erosion, and abrasion protection afforded by even a thin coating of diamond. The erosion resistance of CVD diamond is significantly superior to that of PCD (high pressure sintered diamond). This superiority stems from the fact that the surface of CVD diamond is 100% dense, without the voids between the sintered grits which are present in PCD's and which afford the erosive medium weak areas to attack and remove diamond grains in PCD's. Erosion tests have experimentally quantified the superiority of CVD diamond over any other material (Table III).

Table III - Erosion Resistance

	Relative Volume Loss
CVD Diamond	1
PCD (Sintered High Pressure Diamond)	4
Tungsten Carbide (6% Cobalt)	120
Alumina (99.5%)	220
Silicon Carbide	360
Silicon Nitride	920

Test Parameters → 2% SiC in Water
→ 300 Ft/Sec.
→ 45° Impingement

3. CVD DIAMOND IN ELECTRONICS APPLICATIONS

CVD diamond has a unique combination of the highest known thermal conductivity with high electrical resistivity and other favorable electronic properties which will make it the enabling material for a new generation of high performance electronics and computer products (Table IV).

Table IV - Properties of CVD Diamond Substrates

Resistivity	$>10^{12}$ ohm-cm
Dielectric Constant	5.6
Loss Tangent	0.0005
Thermal Expansion (RT - 400°C)	2.6×10^{-6}/°C

The first thermal management applications for CVD diamond have been as a replacement for natural Type IIa high thermal conductivity laser diode heat sinks. AT&T recently reported a volume application of CVD diamond substrates for cooling high power laser diode heat sinks.(3)

Another recent commercial development has been the production of microwave test systems for the General Dynamics F-16 fighter aircraft using CVD diamond. The diamond heat sink material replaces conventional ceramic substrate material for this package to dissipate power from small monolithic microwave integrated circuits (MMIC). The test package has been greatly simplified, reducing the overall cost and increasing reliability.

As the power of future single chip packages increases to 20W and then to 50-100W, diamond substrates will play a large role in controlling heat rise and device reliability.(4) Similarly, the benefits of diamond have been measured in the thermal management of power semiconductor devices such as MOS-controlled thyristors (MCT) and insulated gate drive bipolar transistors (IGBT).(5)

The most important new application of the large diamond substrates is expected to be in high density, three dimensionally interconnected multichip modules (MCM's) in high power computers. Until the recent development of CVD diamond wafers (Figure 1) of diameter greater than 10 cm, thicknesses of 1 mm or more, and finished surface roughnesses less than 0.2 microns Ra, this new technology could not have been conceived.

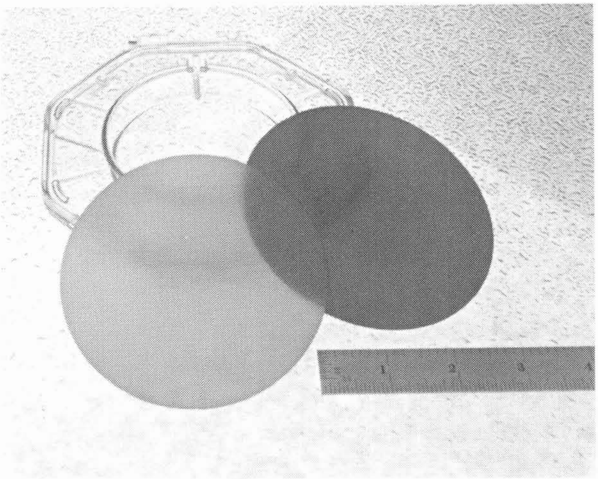

Figure 1. Diamond wafers 10 cm in diameter for thermal management. The lighter disc of "white" diamond may be polished to produce optical windows.

Eden[6] and others[7] have shown how vertical interconnects between 100 mm x 100 mm diamond MCM's of high thermal conductivity can increase the system clock rate from 250-300 MHz to almost 1 GHz by cooling each substrate from only two edges, even while dissipating as much as 500W per board. It will be possible with this technology to package the processing power of a 16,000 MFLOP, 8000 MIP's instruction rate machine (a supercomputer) into a 10 centimeter cube. Diamond is the only material which can enable this extremely high packaging density and clock rate. As the cost of diamond decreases and the areas of application expand, the diamond MCM market is expected to grow to the billions of dollars.

Perhaps the best evidence for the high quality achievable with CVD diamond comes from the recent development of electronic grade diamond suitable for nuclear particle detector use. Diamond has greater radiation hardness, and superior theoretical performance potential as a particle detector material than silicon.[8] CVD diamond has been grown which has a charge collection distance several times greater than that of natural Type IIa. Furthermore, surface photoconductivity measurements indicate a carrier mobility comparable to the best natural diamond. This exceptional performance provides proof that CVD diamond can be grown to extremely high quality levels, even to the quality level required for semiconductor applications.

4. SUMMARY

The potential for this revolutionary new material is very exciting. It's range of applications extends from reducing the cost of products made from new aerospace materials, to new biomedical applications which take advantage of its chemical inertness, to making possible the next generation of compact high performance computers. Anyone who works with materials may find benefit in applying the new CVD diamond technology to solve their materials problems.

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