

State-of-the-art synthesis and post-deposition processing of large area CVD diamond substrates for thermal management

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Abstract

Primarily due to its outstanding thermal conductivity and high electrical resistivity, diamond is an ideal heat spreader for a variety of applications such as multichip modules (MCMs), laser diode arrays, power modules, etc. For these and similar applications, there is a requirement for the synthesis and post-deposition processing of high quality, stress-free, large area (1–100 cm²), CVD diamond substrates. Although the thermal characteristics of CVD diamond are primarily determined by proper nucleation and growth conditions, post-deposition processing such as polishing, planarization, drilling/cutting, and metallization are required for the practical application of diamond as a heat spreader. Such processes should be fast, compatible with conventional electronic packaging, adaptable to large area fabrication, environmentally-safe, and economically-viable. In the past few years, significant technological advances have been made in all these areas. Furthermore, the cost of these processes has been decreasing steadily so that fabrication of diamond-based electronic products is becoming affordable. This paper reviews the present technological and economic status of CVD diamond for thermal management applications.

Keywords: Synthesis; Post-deposition processing; Cvd diamond substrates; Thermal management

1. Introduction

Rapid changes in the electronics industry are driven by the attractiveness of smaller, faster, and lighter weight electronic systems. Consequently, multichip packaging technology is receiving widespread attention. The use of multichip modules (MCMs) promises to increase packaging density and system performance beyond what is otherwise possible with advances in VLSI and surface mount technology. As is the case for most advanced technologies, the drive towards high performance multichip modules has given rise to a number of engineering challenges. In advanced electronic packages, where high speed, high power chips are mounted shoulder-to-shoulder on large circuit boards, heat spreading and removal become major issues. Typically, thermal management substrate materials for electronic packages have been limited to silicon, alumina, and to a much lesser extent, AlN, SiC, and glass/ceramics. However, as the power dissipation of ICs continues to increase,

heat dissipation and removal will be major issues in future MCMs. More than likely, diamond will play a significant role in the solution to these performance challenges.

1.1. Why diamond for heat spreaders?

For the single chip or multichip module, or any high density electronics packaging to be successful and reliable, efficient thermal management (TM) is essential. Diamond has an excellent thermal conductivity ($k = 2000 \text{ W/m}\cdot\text{K}$) for natural diamond and about 700–1600 W/m·K for CVD diamond, a low thermal expansion coefficient ($\approx 10^{-6}$), high electrical resistivity ($> 10^{12} \Omega\cdot\text{cm}$), and high mechanical strength (Young's modulus $\approx 10^{11} \text{ Nm}^{-2}$). These properties of diamond surpass those of all the established substrate materials such as copper, silicon, alumina, aluminum nitride, etc., and make it an ideal heat spreader. Recent advances in CVD diamond deposition technology make it possible to fabricate large area (10 × 10 cm) diamond substrates in the laboratory at a reasonable cost. The availability

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of such freestanding diamond makes possible the practical implementation of such a novel heat spreader.

1.2. Thermal considerations

In the investigation described here, a popular software package, ANSYS, (version 5.0SASI, Houston, PA), which employs the finite element method for thermal simulation, was used to observe the effects of substrate thickness parameters on TM [1]. It was assumed that the contact resistance between materials (for example, an IC and the substrate) is zero. Also, heat loss due to radiation is neglected. For all simulations, the substrate was assumed to be a square with each side being 10.16 cm in length. The power dissipated on the top surface of the substrate was 10 W cm^{-2} for a total power of 1032.256 W dissipated uniformly on an area of 103.2256 cm^2 . This is an extreme situation for most electronic packaging applications. The two opposite edges were kept at a constant temperature of 300 K with adiabatic boundary conditions applied to the other two edges and the bottom surface of the substrate. Thus, the maximum temperature rise is expected to be in the center with isotherms parallel to the two opposite edges held at 300 K. For calculation purposes, the thermal conductivity (k) of the diamond substrate was assumed to be isotropic thus avoiding any thermal resistance caused by grain boundaries in the diamond.

Fig. 1 is a plot of the maximum temperature as a function of diamond thickness for the simulation conditions noted above. The thermal conductivity was assumed to be $1500 \text{ W/m} \cdot \text{K}$. As the thickness of the diamond increases, its contribution to the reduction of temperature becomes smaller. This trend has an important implication in determining an optimum value for the thickness of the substrate. Currently, a substrate thickness considered sufficient for MCM application is typically $1000 \mu\text{m}$. According to the simulation results, diamond substrates 20–30% thinner can be used with

similar TM performance. For example, the rise in temperature for a diamond substrate of $800 \mu\text{m}$ thickness under the conditions noted above is 107.54 K. This result suggests that the cost of growing CVD diamond can be reduced by limiting the thickness of a substrate to the maximum value required for a specific application.

1.3. CVD diamond substrate fabrication-related problems

1.3.1. Diamond synthesis

In state-of-the-art synthesis, CVD diamond films are deposited at high temperatures ($>750^\circ\text{C}$) either by localized or bulk heating in a mixture of a carbon precursor gas (methane, acetylene, etc.) and a graphite etchant gas (hydrogen) in the presence of an activation agent(s) such as IR radiation, microwave radiation, a d.c. arc, r.f. radiation, or a laser(s) [2]. Presently available CVD diamond equipment, such as d.c. arc jet, microwave plasma, and r.f. plasma systems, are capable of growing diamond films as large as $10 \times 10 \text{ cm}$. However, films synthesized using various types of activation agents typically have chemical and morphological non-uniformities over the surface and throughout the volume of the material [3]. Also, large diamond substrates can exhibit high intrinsic stresses that result in warping unless deposition conditions are tightly controlled. In general, the higher the thermal conductivity, the higher the stress. This limits the range of thermal conductivities available for large area, thermal management substrates [3].

These techniques are used to deposit diamond over larger and larger areas in order to reduce the cost (per square) of the material. This approach does decrease the cost to some degree, but it also introduces the need for a laser cutting capability in a manufacturing process which presents an added expense. Another factor that must be addressed is the fact that electronic packages are available in various shapes, sizes, and materials

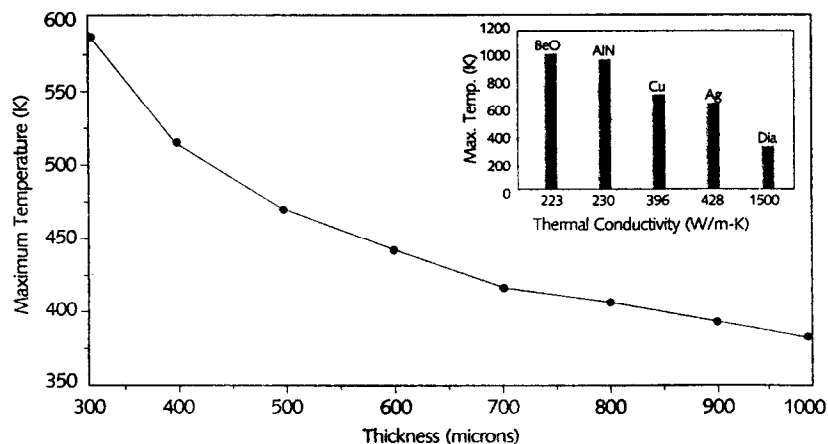


Fig. 1. Plot of maximum temperature vs. diamond substrate thickness for $k = 1500 \text{ W/m} \cdot \text{K}$.

which requires a capability for depositing diamond onto different materials of both flat and complex geometries.

1.3.2. Diamond post-synthesis processing

Diamond growth in the initial stages of deposition progresses by nucleation at mechanically-induced and/or randomly-seeded and/or thermally-favored sites because of statistical thermal fluctuations at the substrate surface. Depending on the growth surface temperature, pressure, and reactive environment conditions, favored crystal orientations dominate the competitive growth process. Consequently, the resulting films have a random polycrystalline structure and a rough surface morphology. Large surface roughnesses ($R_a=2\text{--}15\ \mu\text{m}$) often limit the TM efficiency of diamond substrates because of large and numerous surface pits which result from the presence of microcavities in the as-grown bulk material [4]. As a result, post-deposition processing is required if CVD diamond is to be used in many electronic packaging applications. Several novel approaches to post-deposition polishing of CVD diamond films have been investigated recently, including laser/ion beam/plasma treatment, hot metal treatment, and chemical-assisted mechanical polishing and planarization (CAMPP) [5].

Unfortunately, these polishing techniques do not eliminate “microcavities” in diamond substrates because diamond crystals grow faster in a direction normal to the substrate surface than parallel to it resulting in columnar growth. During growth, these crystals grow into each other creating microcavities throughout the material (Fig. 2). The presence of microcavities prevents any polishing process from yielding a pit-free surface. This, in turn, presents serious problems for photolithographic processes, such as the formation of metal traces, and die bonding in applications requiring uniform thermal contact between the die and substrate. These surface

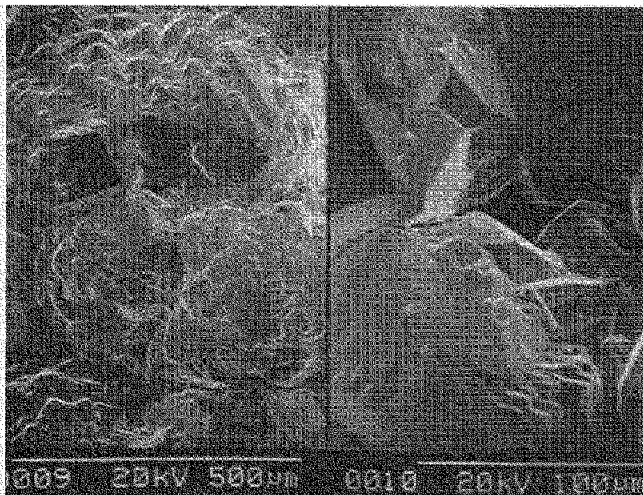


Fig. 2. SEM micrographs of microcavities in CVD diamond.

pits also present a problem for attachment of large die by introducing stresses. Furthermore, the sharp edges of the microcavities lead to an increase in surface non-uniformities after electroplating of a metal layer [6]. The size and density of these microcavities can possibly be reduced, but not eliminated, by increasing the density of nucleation sites on the substrate and depositing at a lower rate. At the present time, the only practical way of eliminating these surface pits is by “filling-for-planarization” [7].

Because of the attractiveness of CVD-diamond for passive electronics applications, reliable metallization systems must be available. Furthermore, in order to produce thick interconnects, plating is the preferred method of applying a metal, such as copper or gold, to the diamond. Unfortunately, owing to its chemical inertness, diamond is expected to have poor adhesion to metals, especially to gold (Au) – a noble metal best suited for conductor traces because of its excellent electrical conductivity. The use of gold, then, requires a metal adhesion/seed layer. Fortunately, diamond is known to form adhering carbide layers with refractory metals such as Ti, W, Mo, etc., and transition metals such as Cr, Ni, Fe, etc. Cr has been used extensively in MCM technologies as an adhesion promoter and diffusion barrier metal and, since it lies close to the refractory metals in the periodic table, it is expected to have excellent carbide forming properties with diamond. Plated gold or copper can then be used to form the interconnections.

2. Experimental

Some of the major steps in the fabrication of diamond heat spreaders are: (1) seeding of substrates for the nucleation of diamond growth, (2) surface finishing of diamond substrates, (3) cutting and drilling of diamond substrates, and (4) metallization of diamond substrates. Subsequent sections address these subjects in some detail.

Raman spectroscopy (RS) was used for the chemical analysis of diamond, scanning electron microscopy (SEM) and/or atomic force microscopy (AFM) were used to study the surface morphology of diamond substrates, and contact surface profilometry and AFM were used for surface roughness analysis of processed diamond heat spreaders. X-ray diffraction was used to determine residual stress in diamond films.

The thermal conductivity of diamond is an extremely important parameter for thermal management substrates. Various techniques, such as the heated bar technique, the Sinku-Riko modified angstrom technique, the Omega technique, the laser flash technique, the transient grating technique, and the photothermal technique, have been and continue to be investigated for

thermal conductivity analysis of heat spreaders. A detailed discussion of these techniques is beyond the scope of this paper, but can be found in a recent publication by Grabner et al. [8].

3. Results and discussion

3.1. Seeding for large area diamond growth

In state-of-the-art CVD diamond deposition, the deposition process is usually initiated by depositing on an iron mandrill or by providing defect sites on a substrate surface. In order to decrease the time necessary to initiate the growth, seeding is often used. This can be accomplished by mechanically abrading the surface using diamond particles to physically generate defect sites. Numerous groups have used this inexpensive approach to accelerate the initiation of diamond growth. Also, small diamond particles, mixed with photoresist, can be uniformly distributed on a substrate surface by spin coating [9]. Once the photoresist is burned off in a plasma, the diamond particles act as nucleation sites for diamond growth. Both of these techniques can be used for small or large area applications. Typically, 10^7 to 10^9 particles cm^{-2} density can be achieved using these techniques. However, a low nucleation density and/or clumping of diamond particles generally results in material with a significant number of large microcavities in the diamond film. Thus, a need exists for a technique which will yield a very high and uniform nucleation density over the entire surface of the substrate onto which diamond is to be deposited. Such a technique should only be limited by the minimum diamond particle size that can be uniformly deposited onto the substrate surface.

3.2. Large area diamond synthesis

Two of the most important requirements for any process for depositing large area diamond films are: (1) a high growth rate (at least $5 \mu\text{m}/\text{h}$) and (2) the capability of depositing uniform films over a large area (at least 6.5cm^2). In the published literature, there are a few techniques being used for the production of thermal management diamond substrates. Some of these techniques are d.c. arc jet CVD, microwave plasma CVD, and hot-filament CVD. Of the other techniques being studied, the most promising approach may be a laser-activated deposition technique. The reported growth rate is about $1 \mu\text{m s}^{-1}$ over a 1cm^2 area [10].

In our laboratory, we have deposited diamond onto silicon using the microwave plasma CVD technique. The deposition system is made by Wavemat, Inc. and operates at the TM 012 mode at 2.45 GHz. In this system, uniform and continuous diamond films have

been deposited over 75 mm silicon wafers using the photoresist seeding technique with 4 nm diamond particles. Nucleation densities of $>10^8 \text{cm}^{-2}$ are routinely obtained.

3.3. Intelligent quality control using optical emission spectroscopy (OES)

An optical emission spectrum of a microwave plasma showing the different reactive species present during diamond deposition is shown in Fig. 3. The atomic traces from hydrogen and the molecular structure from CH, C_2 , and H_2 are clearly visible. However, these transitions only provide direct information for the excited states. To infer information related to the chemically-important ground state densities, a knowledge of the electron energy distribution function (EEDF) is needed. Using argon as an actinometer, we can study the population of ground state atomic hydrogen. Because OES is relatively easy to implement, the determination of in situ correlations between OES and diamond growth parameters is of great interest. Numerical simulations which account for the non-Maxwellian EEDF will facilitate this determination.

Our present actinometry data show that increasing methane concentrations depress the EEDF and negligibly affect the atomic hydrogen ground state. The effect on the EEDF presumably results from increased electron-molecular vibrational coupling. Our data also indicate that increasing power increases the atomic hydrogen ground state density but only marginally increases the energy of the EEDF. Numerical simulations have been combined with experimental optical emission measurements of free and bound-excited electron number densities to demonstrate the potential of OES as a quantitative diagnostic tool for microwave CVD reactors [11].

3.4. Cutting and drilling of diamond substrates

Cutting of CVD diamond substrates is an essential step in the fabrication of thermal management substrates. Free-standing diamond substrates are usually manufactured by deposition over a large circular mandrill and often have a lip (or collar) around the outer edge caused by deposition on the edge of the mandrill. This creates a need for a method of cutting substrates into either circular wafers without the collar or substrates of various other sizes and shapes. However, the cutting of single-crystal gem diamond and polycrystalline CVD diamond is different in several respects. The hardness and chemical inertness of CVD diamond, along with its polycrystalline structure, present a serious challenge to conventional substrate cutting techniques. The problem is even more complicated if one desires to cut thick diamond films deposited on a substrate with

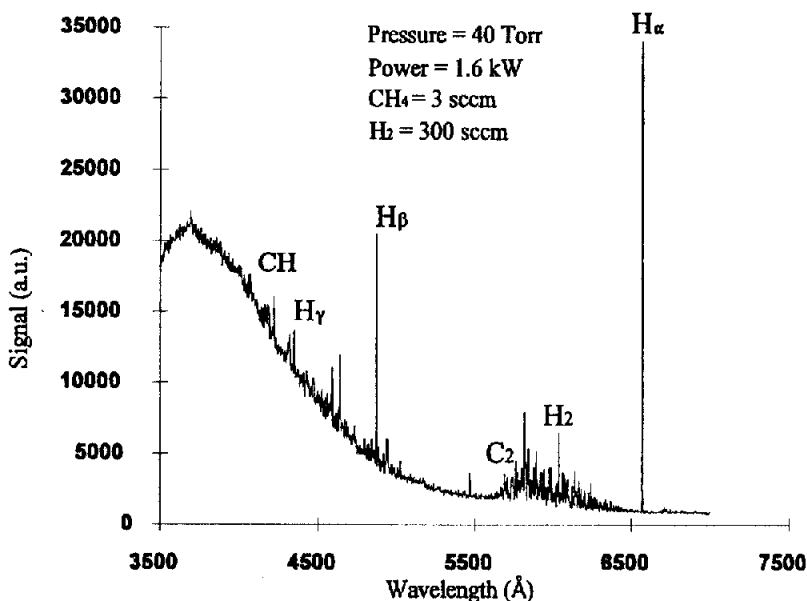


Fig. 3. OES spectrum of a typical 1.6 kW microwave plasma with H_2 and CH_4 gases.

different thermal properties. In fact, although diamond cutting technology is new to the CVD diamond industry, it was developed a few decades ago for cutting single-crystal diamond slabs (not gems). Typically, CVD diamond is cut using a pulsed Nd-YAG laser. The wavelength, power, and repetition rate of the laser, and the chemical quality of diamond, critically determine the definition of the cut, i.e., the cutting-induced burr, the contamination, melting, and refusing of the material, and micro-cracking of the material. Also, the definition of a corner can depend on the proper choice of laser wavelength. Furthermore, the cutting speed of a laser can be enhanced by providing proper photo-chemistry or certain gases at the workpiece.

The formation of vias for substrate-to-substrate interconnects is another important technology in a series of processing steps necessary for the fabrication of diamond substrates, particularly 3-D multichip modules (MCMs). Vias, which are typically 100–150 μm in diameter, are filled with metal to define metal interconnects through the diamond plane. Depending on the size and design of an electronic system, the number of vias can vary from a few hundred to a few thousand on a single substrate and diamond, due to its hard and chemically-inert nature, presents a formidable challenge to their formation.

Laser drilling is the only practical approach to the formation of vias in CVD diamond. The challenges are to form very precise diameter vias in a short time with a desirable edge angle, little, if any, wall contamination, and excellent definition of the top surface-hole wall junction. A further complication in state-of-the-art CVD diamond substrates is the existence of internal stresses. Drilling of a substrates changes its stress pattern, and

thus, the flatness of the substrate. Although, a significant amount of research has been conducted in this area, very little has been published because the techniques used and results are considered proprietary. A most promising approach to this problem consists of drilling the film while it is submerged in a liquid using a focused Q-switched Nd-YAG laser. To date, drilling has been performed in air, de-ionized water, and a few other solutions (Fig. 4) [12–16]. Research on this approach to via drilling of diamond is continuing.

3.5. Lapping and polishing

The chemical inertness, hardness, polycrystalline nature, and non-uniform surface chemistry of CVD

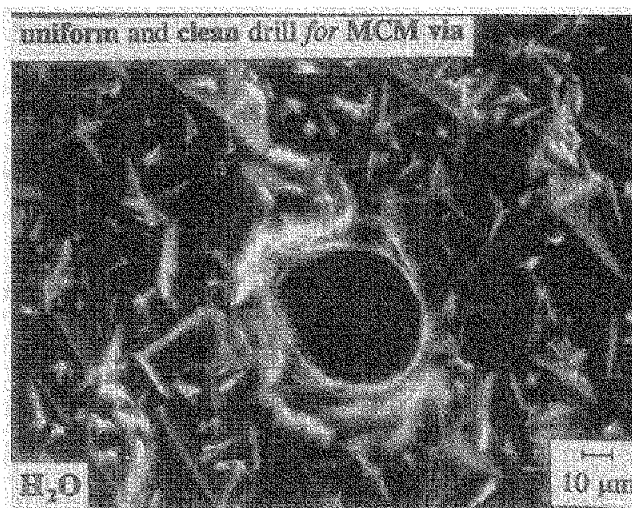


Fig. 4. SEM micrograph of a laser drilled hole in CVD diamond performed under water.

diamond present serious challenges to the development of surface finishing processes (i.e. polishing and planarization). Techniques which have been tried include conventional mechanical lapping, hot metal polishing, chemical-assisted mechanical polishing, plasma etching, ion beam etching, and laser beam trimming. In general, these approaches can be divided into coarse lapping and fine polishing. For example, mechanical lapping and laser trimming can be used to produce a coarse finish (Fig. 5). Using these approaches, the surface roughness of diamond can be reduced from an R_a of 15 μm to about 1–1.5 μm as determined by contact surface profilometry. If an electronic packaging application requires a further reduction in the surface roughness, a technique such as chemical-assisted mechanical polishing can then be used for fine polishing. This technique is capable of reducing the average surface roughness from an R_a of 1.5 μm to about 100–150 nm as measured by contact surface profilometry [16]. Table 1 provides a comparison of the capabilities of these lapping and polishing techniques.

As noted previously, a close examination of even finely polished diamond surfaces ($R_a = 50$ nm by contact surface profilometer) using AFM reveals the presence of surface pits resulting from “microcavities” being intersected by the surface plane. Microcavities have been observed in all CVD diamond material independent of the deposition technique. Often, these surface pits are not detected by contact surface profilometry, but they exist and must be addressed by some post-deposition processing technique.

3.6. Planarization-by-filling

Basically, the “planarization-by-filling” process consists of filling diamond substrate surface pits (microcavi-

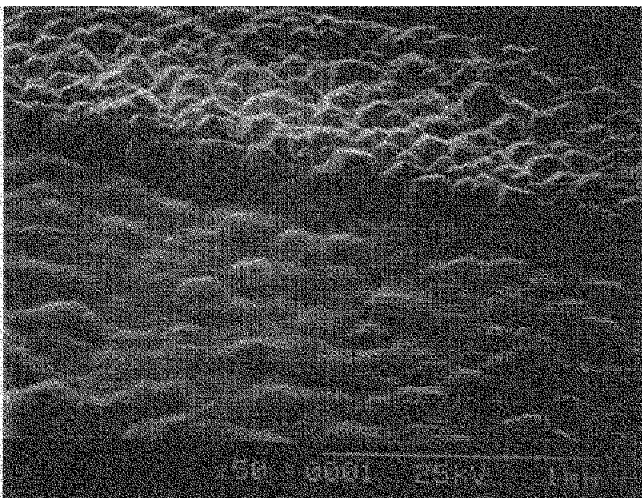


Fig. 5. SEM micrograph showing as-deposited and laser trimmed (polished) CVD diamond.

ties) with a polymer, glass, diamond-filled glass, or similar material [7]. The filler is applied as a thin overlayer on the diamond substrate which planarizes the surface. The overlayer can then be polished back to expose the previously polished diamond surface. However, thermal simulation studies of such planarized diamond surfaces have shown that backpolishing is not necessary from a thermal performance point of view. In fact, this planarization technique offers a simple, conventional approach to the reduction of surface roughness without polishing the diamond surface at all, thereby significantly reducing the time and cost of preparing CVD diamond films for electronic packaging applications.

Fig. 6 shows an AFM plot of a diamond substrate which was coated with polyimide prior to evaporating and defining an aluminum pattern on the surface. The polyimide is about 5 μm thick with an average surface roughness of 25 nm. Testing of the polyimide overcoat yielded an adhesion strength value of about 2500 psi. Although the adhesion strength degraded with thermal shock testing, it was still sufficient for use of the planarized diamond substrate in thermal management applications. Fig. 7 shows a planarized and metallized diamond substrate.

3.7. Metallization

3.7.1. Metallization of large area diamond substrates

Diamond MCMs require complex metallization systems for defining the ground and power planes, and the signal interconnects. In order to realize these required electrical functions, large area metallization, selective metallization, and metal via filling capabilities must be available. In particular, gold (Au) or copper (Cu), due to their low resistivity, are considered to be the ideal metals for MCM interconnects. Depending on the MCM performance requirements, the required metal thickness can range from a few microns to a few tens of microns, and the required interconnect width can be a few tens of microns. For such requirements, plating is preferred over thermal evaporation or sputtering because it is a simple and economical technique. Large area plating processes have been developed for both gold and copper at the University of Arkansas.

The adhesion of metallization to diamond in MCMs is a reliability concern. Consequently, the adhesion of Au or Cu to diamond must be enhanced by the use of other metals as seed layers prior to plating. It is important to note that the surface pits discussed previously can cause serious blistering of the plated metal if the plating is not performed properly (Fig. 8). However, “planarization-by-filling” can be used to eliminate the blistering problem.

Table 1

Cost analysis for post-synthesis finishing of CVD-diamond substrates: estimated costs for various processing technologies

	Cost-related parameters (for 3" × 3")			
	LT (8 h day ⁻¹ operation)	CAMPP (8 h day ⁻¹ operation)	Cleaning (8 h day ⁻¹ operation)	FP (8 h day ⁻¹ operation)
1. Capital cost plus % for installation (% capital cost increase for 4" × 4" sample)	\$75 000: laser + table + optics (0%)	\$47 000: machine + accessories (27%)	\$5000: glassware (50%)	\$4800: spinner + IR oven + soft bake oven (10%)
2. Type of consumable	\$120 year ⁻¹	\$4800 year ⁻¹	\$6000 year ⁻¹	\$5000 year ⁻¹
3. Maintenance	\$600 year ⁻¹	\$180 year ⁻¹	\$60 year ⁻¹	\$600 year ⁻¹
4. Energy usage	100 W	2.5 kW	80 W	60 kW (ovens)
5. Time for processing/sample	40 min	3 h	30 min	3.30 h
6. Rigidity of equipment (i.e., vacuum, and critically)	Atmospheric process, critical optical alignment	Atmospheric process, critical sample mounting	None	None
7. Down time to repeat this same process	5 min	30 min	5 min	2 min (final process)

LT, Laser trimming; CAMPP, chemical-assisted mechanical polishing and planarization; and FP, filling for planarization.

Diamond substrate material specifications: (1) substrate size: 3 × 3 in²; (2) initial $R_a = 3\text{--}5\ \mu\text{m}$ (measured by mechanical surface profilometry); (3) final $R_a = 0.25\ \mu\text{m}$ (measured by mechanical surface profilometry); (4) starting thickness, 90 μm ; (5) final thickness, 700 μm ; (6) bow in the substrate, $\leq 25\ \mu\text{m}$; (7) chemical quality (in terms of thermal conductivity), 12 W/cm² · K; (8) primary film orientation, (110); (9) substrate without collar; and (10) grain size variation, 20–25%.

3.7.2. Adhesion/seed layers and metal plating

Owing to its chemical inertness, diamond is expected to have poor adhesion to most metals, especially to gold – a noble metal best suited for conductor traces because of its excellent electrical conductivity. Thus, there is a need for a metal adhesion/seed layer as noted previously. Fortunately, diamond is known to form strongly adhering carbide layers upon annealing at high temperatures (700–900°C) with refractory metals such as Ti, W, Mo, etc., and transition metals such as Cr, Ni, Fe, etc. [17].

Some of the metal systems examined for potential use as the adhesion/seed layer for diamond-based MCM metallization systems are Au/Ti, Au/Ti–W, Au/Cr, Au/Ni–Cr and Cu/Cr. These metal systems are generally deposited by evaporation or sputtering and then annealed at temperatures ranging from 150 to 500°C. Depending on deposition parameters, such as deposition rate, substrate temperature, pressure, etc., adhesion values ranging from about 3 kpsi to greater than 10 kpsi have been achieved [18]. These adhesion values are more than adequate for MCM metallization although they can be increased by sputter etching of the diamond surface prior to deposition of the metals.

3.7.3. Electroplated gold

Although gold and copper plating are mature technologies that have been used in the electronics industry for decades, bare, polished, MCM grade CVD diamond, with its rough surface due to the presence of surface pits, presents a plating challenge. If plating of diamond is attempted using the parameters specified by plating solution manufacturers, the roughness of the diamond surface is enhanced. For example, in initial attempts at gold plating of diamond at the University of Arkansas,

the surface roughness increased from 330 nm to 2 μm for a 4 μm thick gold layer. This surface roughness is unacceptable for MCM substrates. A thorough investigation revealed that the increase in surface roughness had nothing to do with the gold thickness but, in fact, was related to the plating current density. The current density recommended by the plating solution manufacturer was identified as the problem. Upon reducing the plating current density by a factor of 10, the surface roughness actually decreased with increasing gold thickness. Doubling of this lower plating current density maintains the original surface roughness while yielding an acceptable deposition rate of 2 $\mu\text{m h}^{-1}$. A 4 μm thick layer has a resistivity of about 4.0 $\mu\Omega \cdot \text{cm}$ which compares favorably with the standard value for gold of 2.2 $\mu\Omega \cdot \text{cm}$.

Large area plating of diamond substrates (10 cm diameter) for MCM applications can be accomplished by evaporating a Au/Cr adhesion/seed layer followed by annealing at a temperature of 300°C (Fig. 9). The samples are then gold plated to a thickness of several microns and annealed at 300°C. This process yields adhesion values greater than 3 kpsi even after the samples are thermally cycled between 150 and –65°C.

3.7.4. Diamond substrate rework

Because of the relatively high cost of diamond substrates, research has also been performed to establish a viable method for reclaiming them after they have been metallized. Two wet processes and a lapping technique were investigated. A wet process consisting of ceric ammonium nitrate, perchloric acid, and water was found to be the most effective method for reclaiming diamond. EDS showed no indication of chromium on the sample

Image Statistics

Z range	2.209 μm
Mean	684.54 nm
Rms (Rq)	293.22 nm
Mean roughness (Ra)	141.42 nm
Max height (Rmax)	2.077 μm
Surface area	
Surface area diff	

Box Statistics

Z range	277.36 nm
Mean	934.20 nm
Rms (Rq)	69.134 nm
Mean roughness (Ra)	27.572 nm
Max height (Rmax)	166.04 nm
Box x dimension	20.706 μm
Box y dimension	13.176 μm

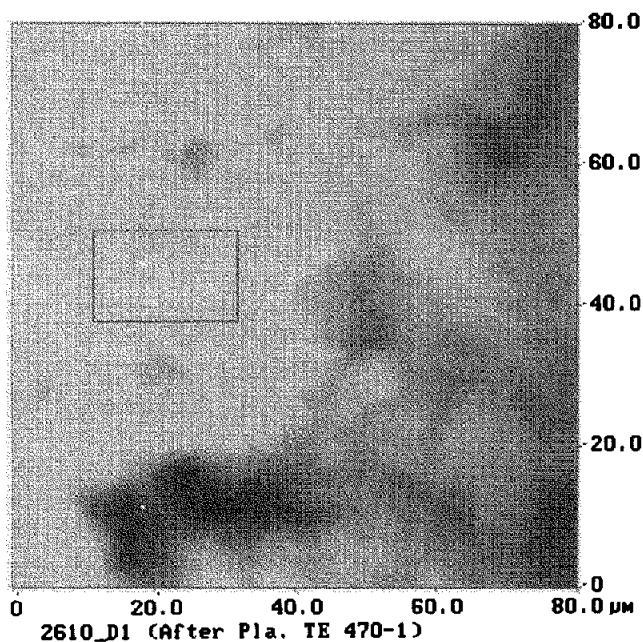


Fig. 6. AFM micrograph of a polyimide planarized CVD diamond substrate.

after an etch time of 15 min in the solution. However, care must be taken to ensure that all the etchant is removed from the sample before it is re-used.

3.7.5. Metallization of vias

Metal filling of substrate vias is obviously important in MCM technologies because of the multi-level nature of the metal interconnection system. Proper via filling is also critically important to multi-substrate communication in a 3-D MCM architecture. For diamond, which has a graphitization temperature between 700 and 800°C, low temperature via filling materials such as metal-filled epoxy or plating can be used. Recently, another approach to via filling using tungsten-copper

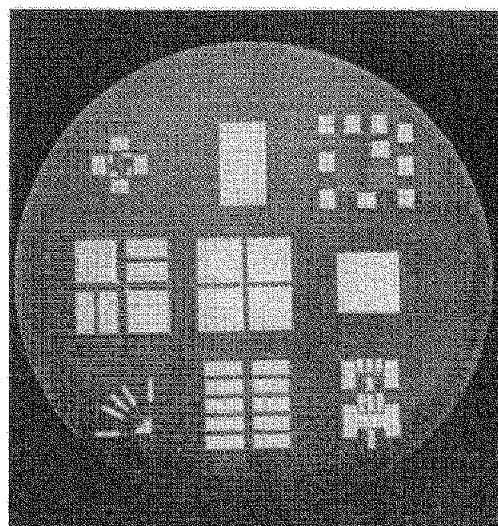


Fig. 7. Optical photograph of photolithographically-defined aluminum patterns on a polyimide planarized 2.0 inch diamond substrate.

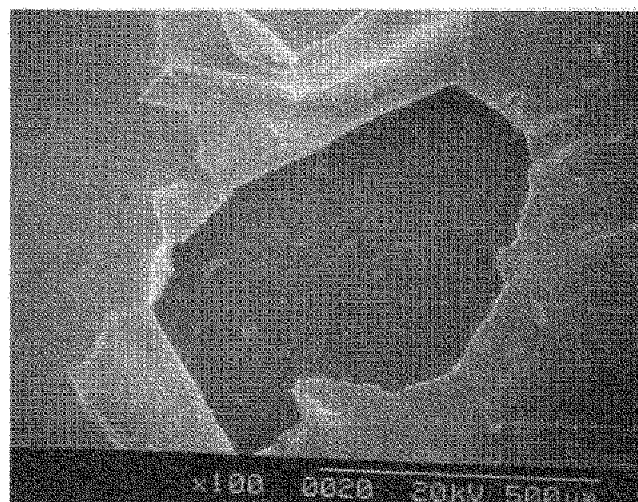


Fig. 8. SEM micrograph of a metallized diamond substrate on which a blister has been deliberately cut open to reveal multiple microcavities.

composite has been developed using a technique developed by Micro Substrates Corporation [19]. Although there are several other approaches to via filling, the method chosen to fill vias in diamond must be based on other construction aspects of the substrate, subsequent processing steps in the fabrication schedule, and the desired function of the vias.

4. Economics of thermal management diamond substrates

At the present time, the electronics industry is extremely cautious about using diamond in packaging because of its cost. As with most products, the introduction of diamond thermal spreaders into electronic products will come down to a trade-off between price and

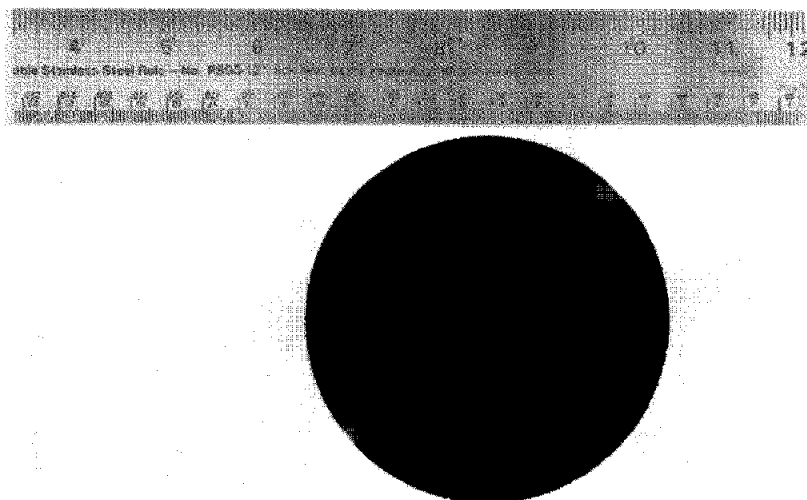


Fig. 9. Optical photograph of a gold plated 4.0 inch diameter diamond wafer.

product performance. This probably means that the initial approach to incorporating diamond into electronics will be applications where the use of diamond is critical for proper system operation and the cost is not a prime consideration. Although diamond heat spreader prices have dropped dramatically in the past few years, a further substantial decrease in price is needed before the widespread use of diamond will occur. For users of diamond, the price depends on the specific application. Questions which must be answered are; (1) can the diamond be used as grown or must it be polished; (2) must the sample be polished on one side or both sides; (3) what is the required surface finish; (4) what is the required thermal conductivity; (5) what is the substrate quantity required; and (6) what are the desired substrate dimensions, including thickness? These questions are very similar to those which must be answered when ordering substrates made from any other material. A 10 cm diameter diamond substrate 1 mm thick contains approximately 140 carats of diamond. As-grown diamond can cost anywhere from \$100 to \$3500 per carat, depending on its quality. Post-synthesis processing such as lapping or polishing add to this cost, and they are very expensive processes. The high cost of post-deposition processing is partially a result of the fact that most vendors are using conventional processing techniques. For example, it takes a long time to lap and polish polycrystalline CVD diamond substrates using techniques developed for polishing gem stones. Non-conventional approaches, such as a combination of laser trimming/quick lapping/filling for planarization are capable of reducing post-deposition processing costs by orders of magnitude as suggested by the data in Table 1.

5. Summary and conclusions

Although technologies for the deposition of thin film synthetic diamond have existed for over a decade, only

in the past 5 years have research efforts been concentrated on economical deposition and post-deposition processing of large area diamond thin films for application in electronic packaging. Because of its unique properties, diamond is the ideal thermal management material if its cost is competitive with other materials and if technologies are available to process it. During the past 5 years, significant advancements in diamond synthesis have resulted in the deposition of large area substrates and a substantial reduction in cost. The availability of large area material prompted a concentrated effort to develop technologies, such as lapping, polishing, planarization, cutting, drilling, and metallization, which would permit diamond to be used in electronic packaging applications. Although not mature, these post-deposition processing technologies have evolved to the point that as-deposited diamond can realistically be utilized in thermal management applications. However, a further reduction in cost of both diamond synthesis and post-deposition processing will be necessary before diamond finds widespread use in commercial electronic packaging.

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