Seki Technotron

Revision 2

TECHNOLOGY OVERVIEW

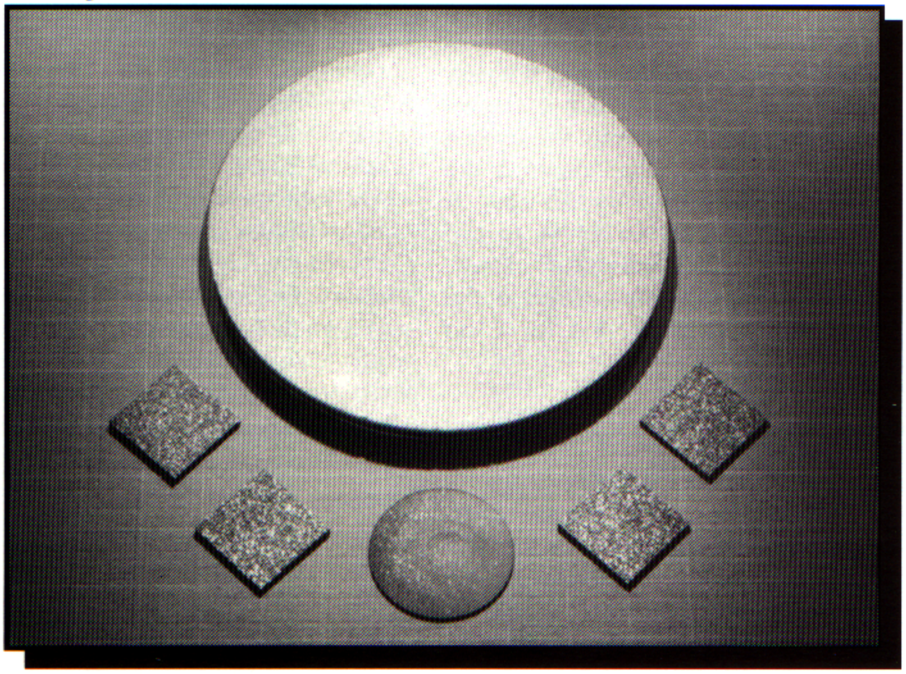
Chemical Vapor Deposition of Diamond Applications to Thermal Management

Introduction

Passive electronic applications of chemical vapor deposited (CVD) diamond films to thermal management are already in the early commercialization stage. In the last few years, CVD diamond films have been deposited which have achieved thermal conductivity values similar to natural diamond (20 W/cm°K). For most heat sink applications, thermal conductivities greater than 8 W/cm°K are adequate, and films which meet or exceed this specification are routinely deposited. These films are commercially available from all the major players in the CVD diamond market: Crystallume, DeBeers, Diamonex, Genasystems, Norton, and Sumitomo.

Natural and high pressure high temperature (HPHT) synthetic diamond heat sinks have been used for years in specialized applications. Their cost increases dramatically with size, and they are not available in sizes beyond a few millimeters. Thick CVD diamond films can be deposited over relatively large areas and, therefore, offer the possibility for new, unique applications such as in laser diode mounts, multi-chip modules (MCMs), surface acoustic wave (SAW) devices, and high power GaAs-based circuits. These films are polished, metallized, and laser cut to the desired size and shape.

Figure 1. Examples of thick diamond films suitable for heat sink applications (the large wafer is 2 in. diameter).



Technical Issues

Thermal conductivity is the most important requirement in thermal management applications. Values in excess of 8 W/cm°K (about twice the value of copper) are adequate and routine in most applications. Higher thermal conductivities are possible but, to achieve them, films must be grown at lower rates. Therefore, production costs increase to the point where film prices can be prohibitive. Films must also be reasonably thick in order to spread the heat properly. As the typical thickness required is 300 to 500 µm, deposition techniques must have high enough rates to keep deposition times within practical limits.

Due to the thickness required for metallization, as-grown CVD diamond has too rough a surface. The substrate side of the film is often smooth but is typically finer grain diamond material with poor thermal conductivity. Thus, films require polishing after deposition (usually on both sides). Polishing

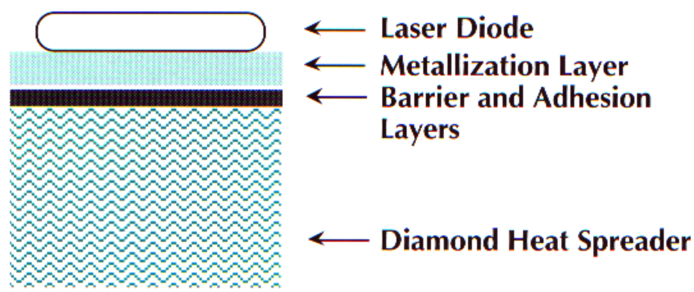


Figure 2. Schematic of CVD diamond used as a heat sink in a laser diode.

significantly impacts production costs, due to the hardness of diamond, and polishing techniques are constantly being developed in an effort to reduce these costs. For successful metallization, the required surface is 0.1 µm rms. Rougher surfaces lead to delamination of the metal layer.

Specifications are quite stringent for flatness and bow of the films. These specifications become increasingly difficult to satisfy as the area of the film increases. Since film deposition takes place at substrate temperatures near 1000 °C, and at high heat fluxes through the substrate, the substrate bows slightly. Even in the absence of film internal stress, as the substrate is separated from the film, the film can bow and typically takes a "potato-chip" shape. The proper design and choice of substrate, in combination with an optimized deposition temperature, can eliminate these problems. Cracks can also develop in the films leading to destruction during the polishing process. This characteristic would have a deleterious impact on yield and, therefore, process techniques which eliminate cracks must be developed.

General Dynamics[1] recently reported using CVD diamond substrates for thermal management in an avionics module for the U.S. Air Force. The thermal properties of diamond permitted a cost reduction of the overall device package even though the price of the diamond substrate was higher than the previous substrate. Similar applications will become more commonplace as engineers become acquainted with the availability of diamond as a substrate material. Sumitomo of Japan has been examining applications of CVD diamond substrates for SAW filters in wireless telephones. This application represents another example wherein the unique properties of diamond make it the material of choice. In this case, a diamond substrate would be part of every wireless telephone built, representing only one example of the potentially large market for CVD diamond substrates.

Thermal Management Market and Players

AT&T announced[2] that thermal management comprised the largest active CVD diamond market today. AT&T estimated their own consumption for 1993 to be on the order of $10M in finished laser diode heat sinks, a significant increase from 1992, estimated at approximately $5M. AT&T estimated their own consumption in 1995 to be $100M to $200M annually, including more complicated diamond substrates. Most major CVD diamond companies, including DeBeers, Diamonex, Genasystems (GE & Asahi Diamond joint venture), Norton, and Sumitomo, offer products in this application area. Most of these companies are presently operating at capacity, and production expansion is occurring at all of them.

For the past several years, the U.S. government, through the Advanced Research Projects Agency (ARPA), has funded the development of CVD diamond for MCMs. ARPA has made a multi-million dollar investment which continues today, and both Norton and Genasystems have participated in this program. In December 1992, ASTeX was awarded a contract with NRL, which is funded by ARPA, to develop low cost diamond substrates for MCMs. This effort is part of ARPA's MCM program.

Diamond Material and CVD Equipment Requirements

In addition to the necessary thermal conductivities, other CVD diamond requirements are:

- thickness in excess of 200 µm — typically 300 to 500 µm
- diamond flatness typically less than 0.001 in. deviation from center to edge (value for a 2 in. diameter sample)
- surface roughness less than about 0.1 µm rms to permit metallization
- 1 in. x 1 in. squares, typically (1 mm x 1.5 mm heat sinks are very common)
- diamond deposition uniformity better than 10% over deposition area to minimize polishing
- raw diamond cost of $100 per carat or less to be competitive.

Each material requirement translates into a performance specification for equipment in this application area:

- Equipment must be capable of diamond deposition at rates typically greater than 5 µm/hr over substrates greater than or equal to 2 in. diameter.
- Substrate sizes on the order of 2 in. diameter address the majority of today's market (small heat sinks representing the largest portion).
- Flatness requirements are achieved through process control or, alternatively, through proper choice of substrate.
- The diamond material must be polished to achieve the necessary surface smoothness, which can add significantly to production costs.
- The uniformity requirement is a consequence of the high cost of polishing the material after growth.

CVD Diamond Production in Seki Turnkey Systems

	AX6350	AX6550
Capital Equipment Depreciation		
Annual cost over five-year period	$64,000	$96,000
Support facilities over five-year period	12,000	12,000
Consumables		
Gas (hydrogen costs dominate)	$3,000	$4,000
Electricity (@ $0.10/kWh)	5,000	7,500
Replacement magnetrons	5,500	7,000
Other Costs		
Service contract	$25,000	$35,000
Cost of capital	20,000	30,000
Space		
100 sq ft at $80/sq ft (complete with facilities)	$8,000	$8,000
Labor		
0.20 FTE for loading and unloading of wafers, reactor maintenance, record keeping, etc. (FTE salary assumed at $30,000/year + 150% OH rate)	$15,000	$15,000
0.10 FTE for supervisor (FTE salary assumed at $50,000/yr + 150% O/H rate)	12,500	12,500
Total Annual Costs	$170,000	$227,000
Total Annual Production in Carats		
(@ 4 µm/hour / @ 7 µm/hour)	875 / 1,750	1,375/ 2,700
Cost per Carat	$193 / 97	$163 / 84

Figure 3. Economic Analysis for CVD Diamond Production in AX6350 and AX6550 Turnkey Systems.

Figure 3 shows a sample analysis of costs. We investigated the costs of CVD diamond on an annual basis, assuming a conservative 85% uptime and operation 310 days of the year for the reactor. Thus, a total of 7,500 hours of reactor operation is possible each year. The system uptime estimate takes several factors into account:

- Turnkey systems permit unattended operation, thus allowing diamond deposition over most of the year.
- Preventive maintenance items
- Unanticipated shutdowns

For this cost analysis, we have assumed typical thermal management quality deposition processes which are capable of 4 µm/hour and 7 µm/hour rates, respectively.

Building costs have not been included in this simplified model. We have also assumed that a diamond production infrastructure would already exist at the customer site to absorb the rest of the FTE labor. Microwave-based CVD diamond deposition technology is a definite economical alternative to both filament- and torch-based deposition systems.

Equipment Capabilities and Status of Process Knowledge at ASTeX

ASTeX offers three diamond deposition reactors: the AX6350 and AX6550 systems already in the market, and the AX6600, an advanced system, operating at an order-of-magnitude higher throughput, which is currently under development. All three systems can provide CVD diamond material for the thermal management market.

Figure 4 shows a typical Raman spectrum for a high quality diamond film grown on the ASTeX AX6350. There is no significant contribution to the spectrum from non-diamond carbon phases usually present at 1550 cm^{-1}.

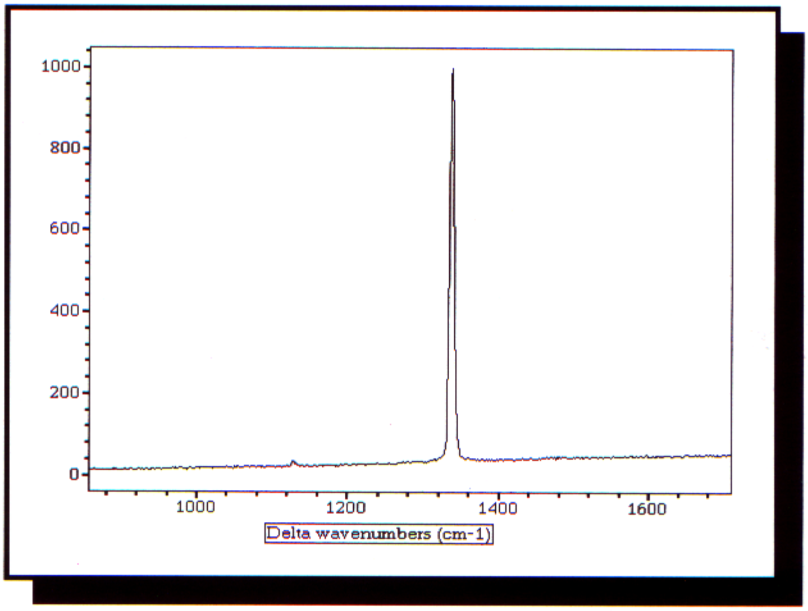


Figure 4. Raman spectrum of thick diamond film.

The AX6350 demonstrated diamond growth rates which were crucial to ASTeX's ability to introduce equipment to this market area in a timely and cost effective manner. ASTeX has already demonstrated that material from the AX6350 satisfies the thermal conductivity criteria stated above. Figure 5 shows independent thermal conductivity measurements on material from ASTeX deposited at several growth rates.

The greatest impact on the price of bulk diamond is still to come. The prospect for lower costs in future advanced systems is excellent, with diamond production costs predicted to drop to less than $10/carat before polishing. Production costs at this level will open up new markets which are price sensitive.

References

[1] P. Lux *et al.*, presented at ICNDST-3 and Diamond Films '92, Heidelberg, Germany, August 31–September 4, 1992.

[2] Wall Street Journal, October 12, 1992.

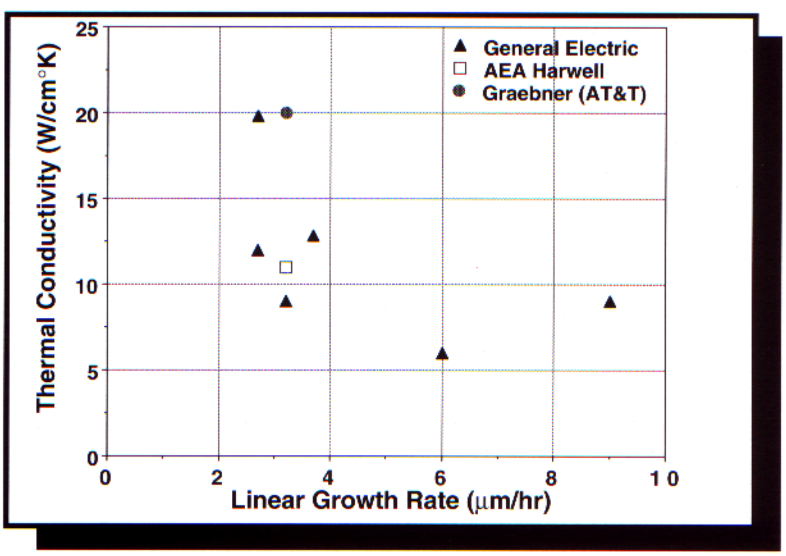


Figure 5. Thermal conductivity data.

SEOCAL Inc.
1153 Bordeaux Dr. #102
Sunnyvale, CA 94089
+1 408 744-9190
www.seocal.com