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Industrial Diamonds: Present and the Future

Three resorting qualities of diamond available today for industrial use are: natural diamond (i), synthetic diamond produced by High Pressure High Temperature (HPHT) method (ii), and synthetic diamond produced by Chemical Vapor Deposition (CVD) methods (iii).

The requirement for industrial diamonds grows exponentially, while the excavation of natural diamonds has a slow linear increase, Fig 1.

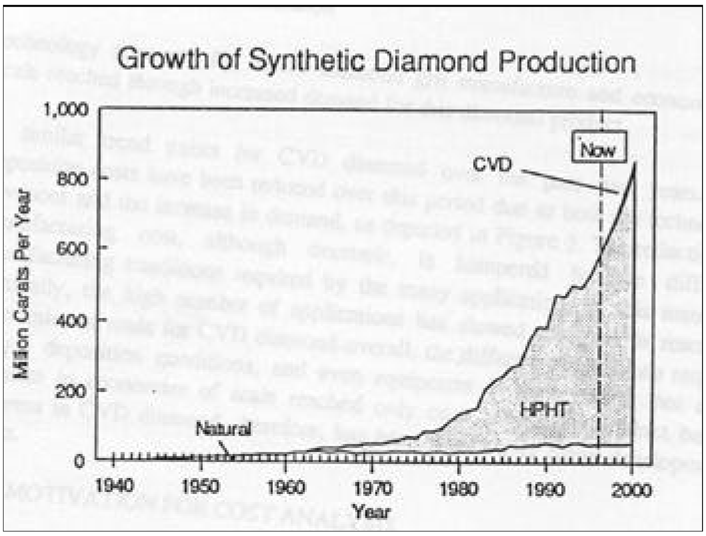

Fig. 1 Growth of the synthetic diamond production (*IBIS Associates, Inc. Economics and commercialization, A.T. Singer and J.V. Busch*)

Natural diamond

Diamonds excavated from earth that have no jewelry quality accounted in the year 2000 for one fifth of 50 tones of industrial diamonds used just for the abrasive needs.

Synthetic diamond produced by HPHT method

The HPHT method subjects graphite to conditions similar to those under which natural diamond is formed in the earth's mantle. The first synthesized diamond by HPHT method was made in General Electric Co, USA in 1955. Under the pressure at the level of 100Kbar and temperature of 2,000^{o}C the individual particles of diamond were synthesized. The most successful synthesis involves growing the diamonds in a flux of molten metal alloy.The average size of particles is approximately 50 microns, with the cost of USA$ 5-10 per gram. The increase of diamond particle size is a great technological challenge and would considerably increase the production cost, Fig.2.

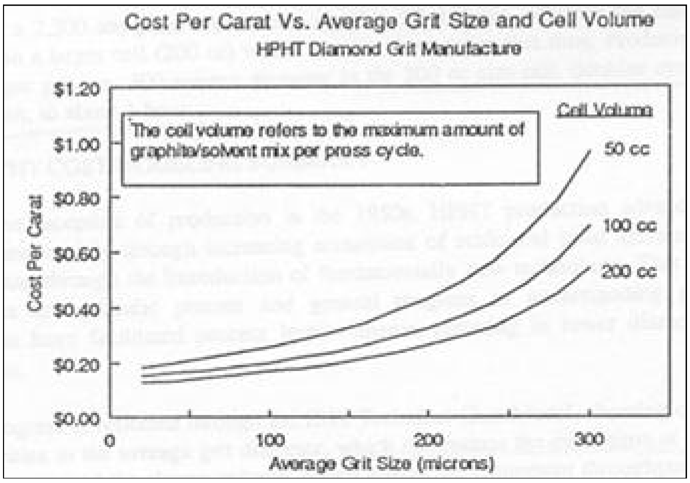

Fig. 2 The cost of the 1ct diamond synthesized by HPHT method *vs* the average grit size (*IBIS Associates, Inc. Economics and commercialization, A.T. Singer and J.V. Busch*)

Synthetic diamond produced by CVD method

Ever since 1983, when Japanese researchers achieved first diamond growth, using a microwave plasma reactor (*Kamo, at al., Crystal, Growth, 62, 642, 1983*), several different CVD methods have been developed for diamond synthesis The principle is to synthesize the polycrystalline diamond from the mixture of a Hydrocarbon gas and Hydrogen, at the total gas pressure below 1 bar and a substrate temperature of around 900^{o}C. Deposited diamond is a film on the surface area up to several hundred cm^2 and, theoretically, of no limited thickness. The CVD diamond is a truly polycrystalline material with a grain structure, growing from small nuclei that inter-grow as they become larger and the layer becomes thicker. Therefore, diamond film exhibits a columnar structure extending upward from the substrate.

CVD methods for diamond synthesis

Four different methods of the CVD have been developed for diamond coating and they differ by the means how a reaction gas mixture heats and activates. Depending on the synthesis method used, the CVD diamond can be engineered to give a range of diamond materials conducive to various new technologies and new opportunities for industry. Main technical and technological parameters pertinent to four different CVD techniques for diamond synthesis are given in Table1.

Table 1 CVD Diamond inputs in years 2001 to 2006

(*IBIS Associates, Inc. Economics and commercialization, A.T. Singer and J.V. Busch*)

	DC Arc jet	Hot filament	Microwave	Combustion
SELECTED IMPUTS				
Wafer Thickness (microns)	500	500	500	500
Thermal Conductivity (W/mK)	1,000	1,000	1,000	1,000
Machine Power (kW)	125	100	500	1,000
Deposition Yield (%)	90	90	90	90

COMPUTED VALUES

Wafer Diameter (cm)	15.2	45.7	57.1	8.9
Deposition Rate (g/hr)	11.8	4.3	7.5	0.4 #
Linear Deposition Rate (µm/hr)	180	7..5	8.3	17
Deposition Cycle Time (hr)	3	67	60	30
Machine cost (USA$/inst)	450,000	600,000	2,194,000	52,000

Due to a much localized – narrow – zone of the combustion torch and rather high linear deposition rate the mass deposition rate of diamond is low.

Four different thermal methods for heating and activation of reaction gas phase are briefly outlined.

DC Arc plasma generates by direct current passing through a gas mixture; heats it and forms very reactive plasma. This method gives the highest deposition rate and the best quality of diamond, primarily due to the high plasma temperature.

Microwave plasma produces through the absorption of microwave radiation by the reaction gas mixture. The method produces the good quality of diamond but deposition rate of diamond is small. Another disadvantage of the microwave plasma coating is the high cost of the installation.

Hot filament uses the glowing filament, which hits the reaction gas mixture. This method produces diamond of good quality but deposition rate is the smallest of the four compared plasma-generating methods, making it cost ineffective.

Combustion flame method enables formation of gaseous chemical species capable of synthesizing diamond. The method uses a very simple and low-cost installation, but the principle shortcoming is the high consumption of expensive gases. The costs of diamonds produced by existing CVD methods are compared in the Fig. 3.

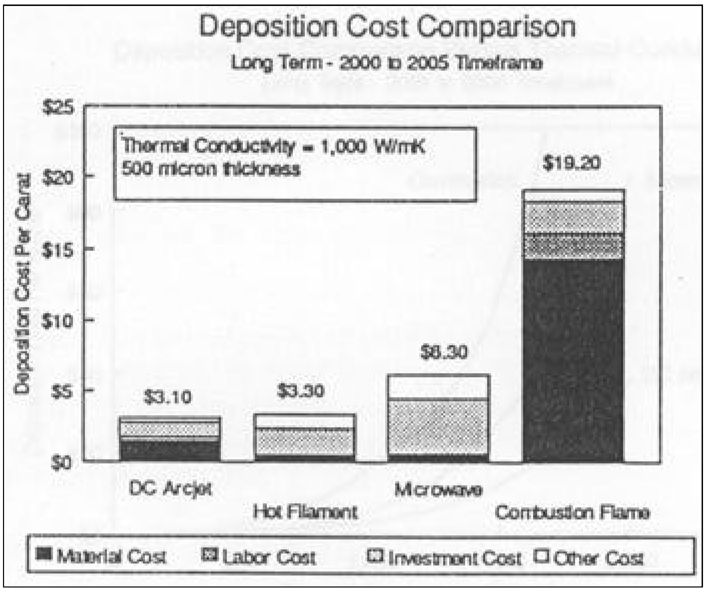

Fig. 3 The diamond deposition cost (*IBIS Associates, Inc. Economics and commercialization, A.T.*

Singer and J.V. Busch).

Properties of CVD diamond

The CVD diamond coating possesses superior physicochemical and thermal properties over all other available materials with similar physical and functional properties. Diamond's most valuable properties such as hardness, Young's modulus, thermal conductivity and thermal shock resistance are compared with the same properties for other materials that are most similar to diamond. The Fig. 4 shows the diamond superiority among the compared materials.

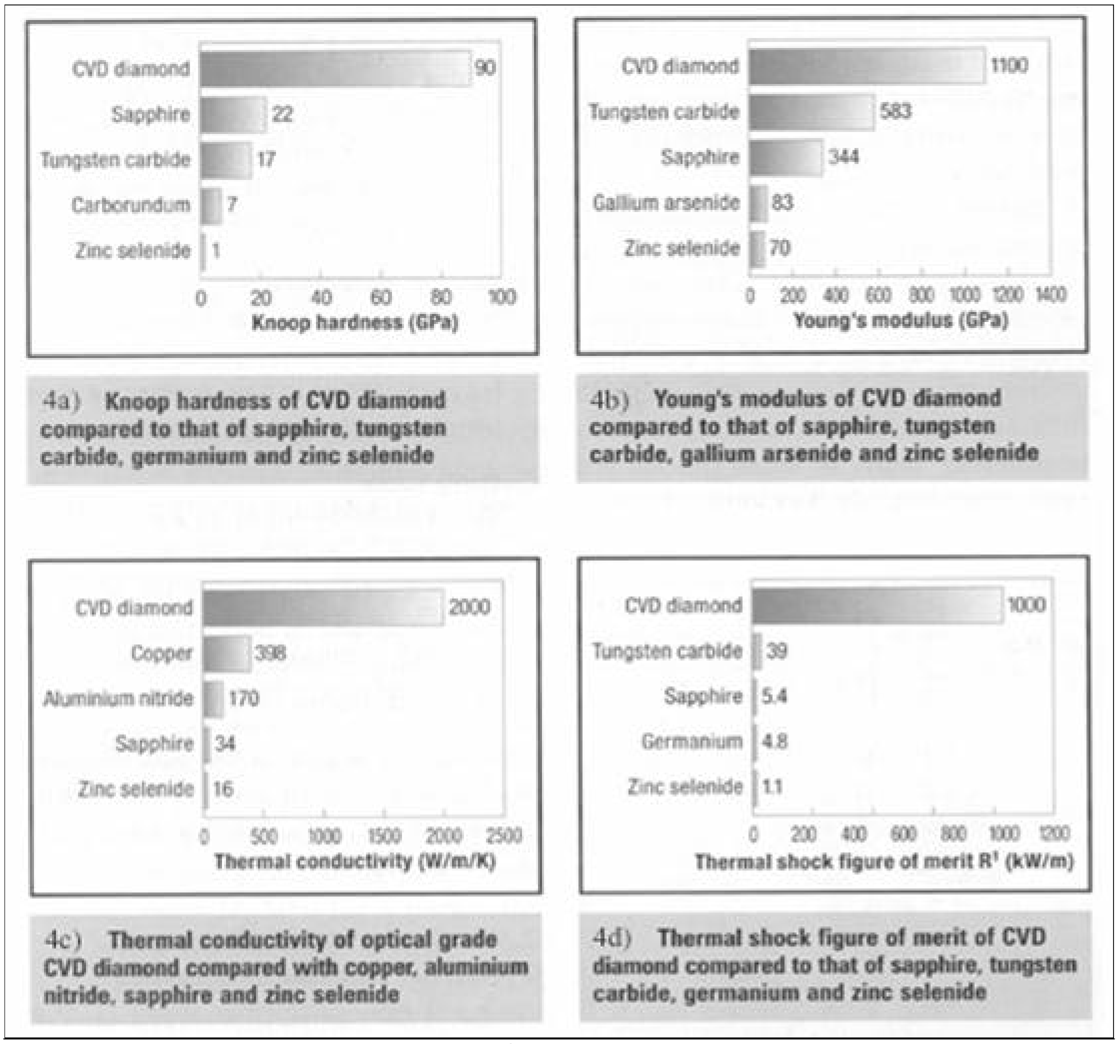

Fig. 4 Physical and thermal properties of the CVD diamonds (*Industrial Diamonds Review, R. S. Sussmann et al., No.4, 2001, p.271*)

Both natural and synthetic single crystal diamonds have measured hardness values dependent on the crystal orientation of the face measured. The Knoop hardness value typically ranges from 57GPa; for the (100) surface to 104GPa, for the (111) surface. Having being fully polycrystalline, the CVD diamond has no single crystal orientation and consequently no orientation's dependence for its bulk hardness which has been measured as 81±18GPa.

Applications of CVD diamond

Development of CVD technologies especially over the last decade has led to the formulation of a range of new diamond materials with properties optimized for specific applications. These include high purity CVD diamond for optical and electronic applications as well as CVD diamond grades suitable for thermal and mechanical use.

The issue, which still prevents the wide-scale industrial use of CVD diamond has been economics; the coatings were simply too expensive compared with existing alternatives. Lowering the cost of CVD diamond coating will make the use of CVD diamond much more economically viable, and finally allow engineers the opportunity to exploit the large array of outstanding diamond's properties in a wide variety of industrial and scientific applications. The following brief outlines list these applications.

Cutting tools The extreme hardness of diamond, coupled with its wear resistance, makes it an ideal candidate for high-performance industrial cutting tools for machining and drilling the demanding materials in the automobile, aerospace and other industries. Not only could the replacement costs of tools be reduced, but so too could the accompanying production downtime that results when toll replacement is required. The feasibility of utilizing diamond-coated tools, however, depends on the ability to apply diamond coatings at a lower cost

Thermal dissipation management Modern high-power electronic and optoelectronic devices suffer severe cooling problems due to the production of large amounts of heat in a small area. And, here diamond coating is excellent material.

Optics Because of its optical properties, diamond is beginning to find uses in optical components, particularly as a free-standing plate for use as an IR window in harsh environments.

Electronic devices The possibility of doping diamond and so changing it from an electrical insulator to a semiconductor opens up a whole range of potential electronic applications. This means that we have a diamond semiconductor and, perhaps, an Intel diamond Pentium chip is the near future in the computer industry.

Surface Acoustic Wave (SAW) device is one type of electronic device which can use impure, thin polycrystalline CVD diamond, as the SAW filter.

Field emission display device is based on the electron emission properties of polycrystalline CVD diamond. It consumes very low power levels, and is the idea of using diamond as an electron emitter in flat-panel displays.

Electrochemical sensors Doped CVD diamond film can be used for electrochemical applications, especially in harsh or corrosive environments. Conducting diamond electrodes, made by boron-doped CVD diamond films, have been found to have a very large potential window in water. This is a great advantage over other electrode materials, such as Pt, which dissociate water at higher electrode potentials resulting in the unwanted evolution of hydrogen and oxygen.

Micromechanical devices and sensors Diamond could also potentially be used in Micro-machines (*Hunn, J. D., at al., 1994 Applied. Phys. Letter,* ***65****, 3072).* The ability to produce thin films which can be precisely patterned; coupled to its stiffness and wear resistance, makes diamond a good candidate for hard wearing micromechanical structures, such as cogs and gears.

Particle detectors One area where CVD diamond is already beginning to find a market is as a ‘solar-blind ’detector for UV light and high energy particles.

Sustainable applications for CVD diamond include tough coatings for drill bits, windows for IR cameras such as those used to detect survivors buried in rubble after earthquakes and heat dissipaters for high power electronic components like laser diodes.

For making wear-resistant coatings, a layer tens of micrometers thick may be enough, while for a window on an infrared camera millimeter-thicknesses would be preferable

Two companies are ahead of others in industrialization of CVD diamond synthesis. DeBeers Industrial diamond group has been developing the microwave method. Their most important result is the window of a 1 MW Gyrotron, Fig. 5. It is a fascinating usage of the synthetic diamond, which was not even imagined before the year 2000. General Electric Co. works with the DC arc plasma technology, and is probably ahead of others in plasma diamond coating.

Fig 5 CVD diamond hemispherical dome, 75mm diameter and 2 mm thick

Fig.5 CVD Diamond hemispherical dome, 75mm diameter and 2mm thick. (*Industrial Diamonds Review, R. S. Sussmann et al., No.4, 2001, p.271*)

Price of industrial diamond and industrial diamond output worldwide

Natural and synthetic industrial diamonds differ significantly in price (*Boucher, Michel, 1996, Overview of the diamond industry, in Industrial Minerals—96 conference, Toronto, October 22, 1996*). Natural industrial diamond normally has a more limited range of values. Its price varies from about $0.30 per carat for abort-size material to about $7 to $25 per carat for most stones. Synthetic industrial diamond has a much larger range of prices than natural diamond. Prices of synthetic diamond vary according to size, shape, crystallinity, and the absence or presence of metal coatings. In general, synthetic diamond prices for grinding and polishing range from as low as $0.09 to $1.00 per carat. Strong and blocky material for sawing and drilling sells for $1.50 to $4.00 per carat. Large, synthetic crystals with excellent structure for specific applications sell for several hundred dollars a carat.

Total 1999 industrial diamond output worldwide was estimated to be well above 570 million carats. Various reports estimate that global output was at least 600 millions carats valued between $600 and $900 million (*Donald W. Olson, Diamond Industrial, 1999, U.S. Geological Survey Minerals Yearbook—1999*). World demand for industrial diamond for abrasive tools and wear parts will continue to replace competing materials in many industrial applications by providing closer tolerances, as well as extending tool life. For example, polycrystalline diamond compacts and polycrystalline diamond shapes will continue to displace natural diamond stone and tungsten carbide products used in the drilling and tooling industries (*Wilson Born, National Research Company*).

The U.S.A. will continue to be the world's largest market for industrial diamond well into the next decade, and it will remain a significant producer and exporter of industrial diamond (*Donald W. Olson, Diamond Industrial, 1999, U.S. Geological Survey Minerals Yearbook—1999*). The most dramatic increase in U.S.A. demand for industrial diamond is likely to occur in the construction sector as the $200 billion if Transportation Equity Act for the 21st Century (*Public Law 105-178; enacted June 9, 1998*) further implemented. The Act provides funding for building and repair of the Nation's highway system through 2003. Demand for saw grade diamond alone is expected to increase by more than $1 billion during the coming years, for the repair and replacement of roads, bridges, and other components in the transportation infrastructure of the country.