CVD GROWN DIAMOND - 2010

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1 Overview

For centuries, diamond's superlative properties have earned it a reputation as the 'dream' material for mankind in its search to create advanced applications. Until recently, this dream has been realized only in the use of diamond for gemstones and abrasive applications where several tons of diamonds are now used on an annual basis.

The vision of having large, high quality diamond as part of a broad engineering tool-kit for many diverse high tech industries is now becoming a reality however, with the advent of early stage commercial availability of single crystal and poly crystalline CVD diamond.

Recent developments in the crystal growth of high quality single crystal diamond via the Chemical Vapor Deposition (CVD) process has allowed device scientists and engineers from many disciplines to think beyond the limitations of HPHT and natural diamond and envision how engineered, pure diamond may be used in advanced applications ranging from quantum computing, to power generation and molecular imaging, and possibly even diamond nano-bots.

2 CVD: A New Growth Phase of Diamond Market Growth

CVD diamonds represent the third and perhaps highest growth phase of the global diamond business. The <u>first phase</u> occurred early in the last century and was driven by mining technology and the consolidation of the diamond mines by Cecil Rhodes. Upon this sourcing consolidation, diamonds became a true global business with product standards and markets becoming common. The 1950's saw the global diamond business expand in its <u>second phase</u> through the advent of High Pressure/High Temperature (HPHT) diamond crystal growth technology. Because of its consistency and cost profile relative to nature sources, HPHT diamond growth technologies propelled diamond to the forefront of many industries. HPHT grown diamond crystals are now a cornerstone the world's industrial base, and the foundation of a global industrial diamond business with multiple billions of carats being produced annually.

CVD diamond represents the beginning of the <u>third phase</u> (and most recent) of the diamond growth path. While early experiments in CVD diamond began in the 1970's, it has only been until recently that pilot quantities and sizes of this extraordinary material have become commercially available. While in its early stages, this phase of the diamond business promises to be the most prolific in its potential and longest lasting, bringing diamond to a ubiquity and impact similar to other fundamental industrial technology materials such as silicon, steel and concrete. The diamond market will grow exponentially from where it is now (albeit in tangential ways) with the new phase of the diamond business growing for the next 50 to 100 years and resulting in diamond as a material used in all parts of our society.

CVD stands for Chemical Vapor Deposition, and it refers to a way of growing diamonds from a gas phase in which large areas of diamond can be deposited and crystals grown. The other interesting features of CVD diamond are its properties which can be adjusted to either include or exclude impurities and additionally change its crystal structure. Single crystal structure and poly crystalline structure of various sizes can now be grown.

The tailoring of CVD diamond properties and the large sizes that can now be grown are key benefits of the CVD growth technology. These process features make diamond very attractive to a wide variety of other industrial fields that previously could not use diamond because of limitations in crystal size, perfection and consistency.

The field of CVD diamond crystal growth is still young, but it is beginning to move into the commercial phase, and advances into manufacturing are occurring at a rapid pace. Demand in traditional markets such as cutting tools and gemstones currently outstrip the capacity of global CVD producers to provide diamond material in sufficient quantities and the prospects for explosive growth remain strong. Some of the most intriguing commercial markets exist in areas of high technology which were outside of the traditional diamond markets. Recent breakthroughs in applications research project CVD diamond having a growth path similar to that of Silicon, finding its way into the next generation of technology applications ranging from quantum computers to solar panels. Diamond will become ubiquitous in our society over the next 25 years.

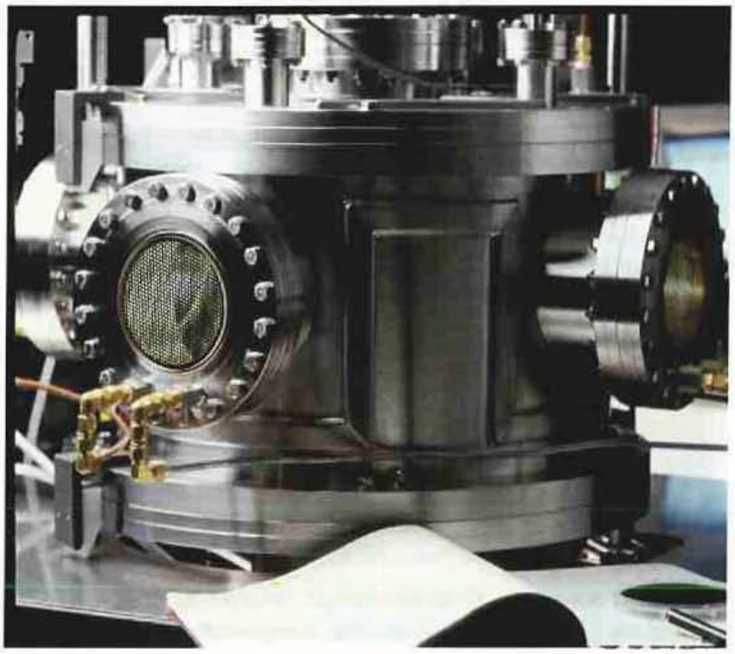
(Apollo CVD Diamond Gemstones)

3 CVD Process and Material

One specific area of the CVD process focuses on growth of single crystal diamonds, the same type of diamond that is found in gemstones mined from the earth. Single crystal diamond grown through this process has exceptional qualities for use in advanced electronics and optics applications. Nonetheless, the superior characteristics of single crystal diamond can only be applied to these applications if the diamond material is consistent in its size and crystal properties. These requirements make the CVD diamond growth process ideal for these high tech applications.

3.1 Equipment and Process

The diamond crystal growth equipment used in the CVD process is both expensive and highly specialized. A standard setup consists of a vacuum chamber, a holder for the diamond, and a heating source to superheat the chamber's atmosphere. In a lab or manufacturing environment, the crystal growth chamber is usually accompanied by some form of laser cutting and diamond polishing equipment to fabricate the diamond in pre-production and post production process. This same set of diamond crystal growth resources can be used to grow either poly crystalline diamond (nano and ultra-nano scale), or single crystal diamond.



(CVD Diamond Crystal Growth Equipment)

When the CVD process is applied to single crystal diamond growth the input materials are a hydrocarbon (carbon and hydrogen) gas, and a seed of diamond. The seed is a thin sliver of single crystal diamond that acts as an atomic template for the ensuing crystal growth. This is necessary as the starting point for all single crystal diamond at this point in time. Generally, you must **start** with a piece of diamond seed and then add to it.

As gas is added to the chamber and heated to temperatures approximating that of the outer areas of the sun, the hydro-carbon gas begins to break down and the carbon atoms attach themselves to the seed of diamond in the vacuum. By managing the growth process the shape of the diamond and its crystal features can be managed to a certain degree. This is important as you can steer the CVD process to impart certain engineered properties to the ensuing diamond for application tailoring. To further tailor the diamond properties, impurities can be selectively and controllably added to the growing diamond by adding gases that contain elements such as boron, nitrogen or phosphorous.

3.2 Fabrications

CVD diamonds can be used to grow thin layers or to create bulk chunks depending on the goals of the crystal growth process. Layers can alternate between intrinsic (pure) diamond layers and layers of doped diamond material, creating features inside the resulting diamond that are unique to the diamond grower's designs. These features and layers may be used to selectively create or relieve strain in the diamond or to create patterns to enable special functions (such as channels or reservoirs).

Note Growth Steps on CVD Material. Shape and size of steps controlled by Chemistry, Substrate Temperature, and presence of impurities

The resulting diamond can be further fabricated post growth via traditional semiconductor process technologies. These processes include more traditional steps such as laser cutting and polishing but also include advance fabrications such as etching, implanting, and photolithography. While early in their development many of the fabrication technologies available to the semiconductor industry are also directly applicable for the processing of diamond.

4 CVD Diamond Crystals: Material Characteristics

Because of ability to engineer and craft diamond growth during the CVD process, a whole new class of diamond materials is emerging that will be relevant to a wide variety of applications.

One way to view the flexibility of the CVD process is to consider some of the process parameters and material properties which can be independently controlled during the crystal growth process. There are three important process control knobs that the diamond grower increasingly has at his/her disposal to prepare the specific type of CVD diamond structure required to meet the needs of the end application. Within the parameter limits of each control knob there is an increasing amount of tuning and precision that is currently being built into the process.

The very concept of how to think about the type of diamonds that the CVD technology enables is in the early stage of developing. This is important in the areas of applications development where business models were built around the scarcity of natural diamonds or the physical limits of size and purity for HPHT diamonds. The new vision is for diamond wafers up to 100 mm wide over the next decade, diamond with controlled and consistent properties, and diamonds structures which are tailored to fully exploit the potential that diamond has for existing and new applications. CVD diamond growth process is the only path for diamonds of consistently large size and low impurities.

(25mm diamond wafer)

Through advances in CVD growth, diamonds are in the process of becoming larger and more ubiquitous, in qualities and characteristics that have just never been available before. Diamonds will in fact change the world and appear in many of the high use applications we take for granted like computers, communications and medical devices. This is the material's inevitable path.

Full utilization will take some time as the CVD process moves into manufacturing volumes but the early results from applications developers are staggering. We are not saying that the world is going to be awash with tons of man-made diamond gemstones either. It is very difficult to grow single crystal diamond thick enough for gemstones. While the world will utilize tens of millions of carats of single crystal diamond for high tech applications, they will mainly be in the form of thin wafers (one quarter to one half millimeter thick) containing internal layers and structures to tailor the properties, and processed through standard semiconductor fabrication processes (such as etching, photolithographic patterning and metallization).

Property	Value
Hardness (kg/mm^2)	10,000
Sound Velocity (m/s)	18,000
Density (gm/cm^3)	3.52
Young's Modulus (GPa)	1.22
Coefficient of Friction	0.02
Thermal Expansion (ppm/°K)	1.1
Thermal Conductivity (W/cm- °K)	20
Debye Temperature (°K)	2,200
Optical Index @ 591 nm	2.41
Optical Transparency Range	UV to far IR
Loss Tangent @ 40 Hz	0.0006
Dielectric Constant	5.7
Bandgap Energy (eV)	5.45
Resisitivity (undoped, Ohm-cm)	10^{15}-10^{16}
Chemical Compatibility	Highly Resistant to Corrosion Bio-Compatible

5 High Growth Applications and Markets

Because of its high utility and projected availability, single crystal CVD diamond will be used in most major application categories. We see most technology vertical market categories consuming large amounts of diamond over the next five to ten years.

Most of these markets have multiple billion dollar sub-components where diamond will yield a significant cost-benefit impact. Some of the areas where we see CVD diamond integration are as follows:

Diamond Property	Application Areas	Function	Impact
Beautiful, relatively scarce, permanent, well-marketed, symbolic significance	Jewelry	Gemstones	+Gem markets
Highest Hardness	Tooling	Wear resistance	+Machine Parts +Superabrasives +Cutting tools, drills +Razors, surgical tools +Cogs, gears, bearings +Aerospace materials +MEMS
Highest Compressive Strength	Machinery	Less lubrication	
Low Thermal Expansion			
Highest Tensile Strength	Composites	Structural strength	
High Thermal Conductivity	Electronic Substrates	Heat Sinks	+High Speed CPUs

Excellent Electrical Insulator	Device packaging	Heat Spreaders	+Laser diodes +Microwave ICs +Small/fast ICs
Excellent Semiconducting Properties, Wide Band Gap	Electronics Computing	Power electronics Wireless devices Optical Communications Semiconductors Ultra-fast switches Transportation Displays, cold cathode devices	+Schottky diodes +High freq FETs +SAW devices +Utility Lines +Ultra-fast computers +Radiation Detectors +Aerospace, Defense +Flat Panel Displays +LEDs, TVs
Negative Electron Affinity (excellent electron emitter)	Switching Photonics		
Excellent Optical Transparency (UV – IR), combined with Durability	Optics	Lenses, Windows Protective Coating	+High power lasers & +IR windows +Optical Components +Spacecraft
Biocompatible, Chemically Inert	Biotechnology Electrochemistry	Sensors Electrodes	+Medical / Implantable +Toxic/corrosive environments +Water/air treatment +Spacecraft

As an example, diamond happens to be the ultimate semiconductor material due to its combination of electrical, thermal, and optical characteristics. Its extreme properties give it unsurpassed utility and performance in thermal management, electrical resistivity, hardness and when doped with boron or phosphorous, electrical conductivity. Until the past few years, tapping these capabilities was thought to be impossible because of the lack of engineered, high quality diamond. Advances in a number of CVD diamond crystal growth programs now make it possible to drive this advanced material into rich opportunity spaces where there is a large need for technical and efficiency improvements.

6 Conclusion

The global economy needs more diamonds than the earth can easily provide and with sizes and purities that are beyond the capabilities of HPHT grown diamond. Diamond technologies will be pulled by the demands of high tech applications to operate faster, more reliably and in extreme environments. These requirements will drive the diamond crystal growth technology to quickly transcend the manufacturing demands currently required by gemstones, and other traditional markets.

(CVD Diamond gemstones, wire-dies and pre-form blanks)

While the industrial support base needs to expand and assimilate CVD diamond and its capabilities, the prospects for extreme growth in this industry are profound. High quality CVD grown diamond material is at the beginning of a fifty to one-hundred year growth curve that will impact our society in a ways similar to that of the Silicon 'revolution' which began in the 1960's.