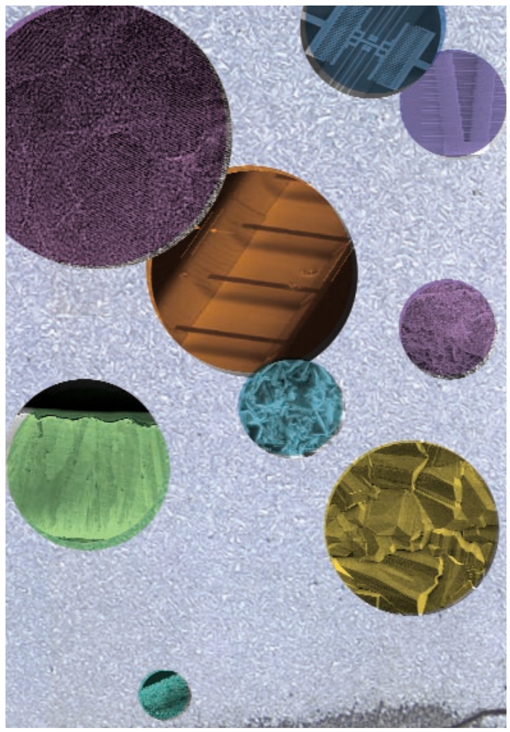
Diamond Science and Technology: Diversity and Maturity

by Greg M. Swain

Through the centuries, no material has been as cherished or treasured as diamond. The outstanding combination of properties has long made it a desirable material for mechanical, optical, and electronic applications. Nature, of course, produces diamond under conditions of extreme pressure and temperature. Driven by greed as well as the challenge, scientists for more than a century have attempted diamond synthesis. The fascinating history of this effort is eloquently chronicled by Robert M. Hazen in *The Diamond Makers*. Much of the historical information I cite below comes from this resource. Attempts to produce diamond began back in the 1820s, and, up until the 1950s, there were really no qualified successes. This was due, in part, to the fact that researchers attempted to produce diamond under conditions of only high pressure, failing to recognize the need for high temperature.



Efforts to synthesize diamond took on added urgency in the Unites States during the late 1940s and early 1950s as Cold War tensions gripped the nation. Diamond was needed for machining and polishing the carbide tools required to fabricate components for war machinery and military hardware. At that time, the country was dependent primarily on imported diamond from South Africa. The Norton Company, General Electric, and Carborundum formed a consortium in the early 1940s with a goal of producing diamond synthetically in order to establish a reliable state-side supply of the technologically-important material. From the mid 1940s to the mid 1950s, the Norton Company led the synthetic effort combining established high-pressure technology and know-how with high temperature processing. For 10 years, scientists worked to grow diamond without success. General Electric, during the 1950s, embarked on an ambitious program to produce diamond, code named "Project Superpressure." The research team met with success in 1954-55, a success that required major advances in high pressure and temperature materials and devices, as well as new insights on the appropriate chemical environment for growth. In 1957, the company began selling "Man-Made Diamonds," its trademarked synthetic diamond abrasive.

The equipment required to produce diamond for high pressure and temperature growth of diamond is expensive and massive in scale. Scientific inquiry to produce diamond at low-pressure, using smaller and less costly equipment, began during the mid 1950s. William Eversole, a scientist at Union Carbide, devised the first reproducible, low-pressure synthesis of diamond in 1957-58. Parallel efforts by the Derjaguin group in the Soviet Union and the Angus group at Case Western Reserve University in the United States in the 1960s further demonstrated that low-pressure CVD growth of diamond was feasible. The work of these researchers provided the foundation for modern day diamond synthesis at low pressures.

Diamond possesses a number of outstanding properties making the material attractive for many applications. Diamond synthesis requires the expertise of physicists, chemists, materials scientists, and engineers. Thus it is hardly surprising that the field of diamond science and technology has permeated the domains of several Divisions within the Society. The Dielectric Science and Technology (DS&T), Electronics, and High Temperature Materials (HTM) Divisions have provided a forum for researchers to present their latest findings at Society meetings through the years, starting in the late 1980s. In fact, the First International Symposium on Diamond Materials (Los Angeles, spring 1989) was, at that time, the largest symposium ever held at a Society meeting. Topics, such as thin film deposition and characterization, corrosion resistant coatings, thermal management, dielectric materials, and high temperature sensors, were regularly covered at Society meetings. Vigorous research was conducted in the United States, Soviet Union, Europe, and Japan, particularly during the 1970s, 80s, and into the 90s. However, the Holy Grail of applications—high power/high speed electronics—remained elusive to researchers. The large breakdown voltage, high electron and hole mobilities, and the high temperature stability are properties that make diamond attractive for this use. Unfortunately, difficulties with depositing low defect diamond in a cost effective manner and controlled *p*- and *n*-type doping have prevented this application from becoming a reality.

Diamond research in these areas continued to advance into the 1990s, less so in the United States and more so in Europe and Japan. During this period, the cost of producing diamond was significantly reduced due to improvements in nucleation and growth rates. More was learned about the mechanisms and kinetics of diamond synthesis. The use of diamond as an electron emitter became an active area of research due to the negative electron affinity of properly treated diamond. Electrically conducting diamond also began being tested in electrochemical technologies. Dimensional stability and chemical inertness are two properties that stimulated the initial activity. Since the first three papers in the early 1990s, there have been over 150 publications to date on various aspects of diamond electrodes.

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A factor limiting the extent of research to date has been the absence of a commercial supplier of diamond electrodes. This situation has recently changed as there are now at least four commercial entities marketing diamond electrodes worldwide.

No other material shows as much versatility as an electrode as does electrically conducting, CVD diamond. The material can be used in electroanalysis to provide low detection limits for analytes with superb precision and stability; for high current density electrolysis (1-10 A/cm^2) in aggressive solution environments without any morphological or microstructural degradation; and as an optically transparent electrode (OTE) for spectroelectrochemical measurements in the UV-Vis and IR regions of the electromagnetic spectrum. The most significant of the published work, so far, has been in the fields of electroanalysis, electrolytic water purification, and spectroelectrochemistry. Therefore, the field of diamond science and technology has expanded so, that some topics now fall within the purview of the Physical Electrochemistry and Industrial Electrolysis and Electrochemical Engineering (IE&EE) Divisions.

The future of the field appears very bright in the opinion of this author. Research and development of specifically engineered diamond for electrochemical electrodes, MEMS devices, electron emitters, dielectric coatings, optoelectromechanical devices, high temperature sensors, acoustic waveguides, etc. will continue to be core areas of research. Electronic applications may also not be far away from reality. Recent advances in the synthesis of low defect, single crystal diamond, controlled doping, and cost-effective deposition are the basis for the cautious optimism. For example, researchers at DeBeer's, employing plasma-grown diamond, recently reported the highest electron and hole mobilities ever recorded for the material—*values that exceed those measured for natural diamond by more than 2!*

The 203rd Meeting of The Electrochemical Society in Paris, France, April 27-May 2, 2003, will include the Eighth International Symposium on Diamond Materials (April 28-29). This symposium will bring together scientists from all over the world to present the latest research in this exciting field. The field's diversity is certainly reflected in the broad range of presentation topics, including electroanalysis, electrolytic water purification, MEMS applications, biomedical applications, surface chemistry and modification, electronic applications, doping and conductivity issues, etc. As has been the case for all previous symposia, a proceedings volume—*Diamond VIII*—will be published and made available to the scientific community. This excellent symposium would not be possible without the generous support of the sponsoring Divisions: DS&T, Electronics, HTM, Physical Electrochemistry, and IE&EE.

The field of diamond science and technology has certainly matured over the years. Some of this diversity is reflected in the four articles included in this issue. James E. Butler of the Naval Research Laboratory, in an article entitled "Chemical Vapor Deposited Diamond: Maturity and Diversity," highlights some of the great progress that has been made in the quality of CVD diamond materials. The article reflects the great flexibility that exists for engineering diamond materials to match the desired properties for an application, such as microelectromechanical systems (MEMS). John Carlisle and Orlando Auciello, of Argonne National Laboratory, discuss the properties of ultrananocrystalline diamond films deposited from CH_4/Ar source gas mixtures and the application of such films in biomedical devices in their article entitled, "Ultrananocrystalline Diamond: Properties and Applications in Biomedical Devices." My coworkers and I, in an article entitled "Diamond Optically Transparent Electrodes for UV/Vis and IR Spectroelectrochemistry," discuss the preparation of optically transparent diamond electrodes for use in UV-Vis and IR spectroelectrochemical measurements. Finally, Matthias Fryda and coworkers, of CONDIAS GmbH, briefly review the deposition of electrically conducting diamond films on high surface area supports for use in electrolytic water purification in their article entitled, "Applications of DiaChem® Electrodes in Electrolytic Water Treatment." ■

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