CRADA Final Report
CRADA No. BG#: 98-084

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2. Title of the Project: **"Advanced Hard Carbon Plasma Deposition System with Application to the Magnetic Storage Industry"**

3. Summary of the specific research and project accomplishments

The goals of this CRADA were defined in the original statement of work as follows:

It is proposed to develop a novel plasma deposition system which allows coatings of computer hard disks and read/write heads with ultrathin (5 nm), diamondlike hard carbon films on an industrial scale.

The development will be based on a new level of understanding of plasma transport which will be achieved by computer simulation and plasma physics experiments. The new deposition system will have the following characteristics:

- virtually complete macroparticle suppression;
- high plasma transport efficiency (we anticipate that the efficiency can be at least doubled compared to present achievements);
- deposition rate that meets present and future expectations of read/write head and disk manufacturers;
- modular design compatible with CSC's Millenium read/write head coater and Intevac's MDP-250 disk coater;
- reasonable cost;
- applicability to large area coatings.

With the exception of the Intevac's MDP-250 disk coater goal, all of the goals have been achieved, in some cases results went beyond the original goals. Specifically, the following milestones were met and results achieved:

1. A new, compact, open-design macroparticle filter was invented, manufactured, tested, and implemented. The design is based on a three-dimensional, twisted S-Filter, or short "Twist Filter" that is characterized by an exceptionally high plasma transport efficiency (about 50%, i.e. doubling the previously achieved efficiency) and virtually complete macroparticle removal. A U.S. patent application is pending.

2. A experimental prototype and later a commercial "alpha" version of a Twist filter coating system were developed at Berkeley Lab and implemented at CSC's commercial Millennium read/write head coater system, located in a clean room of Read-Rite Corporation, Fremont, California. (Read-Rite is a customer of CSC). The prototype "alpha" version included a number of innovative designs such as an advancing cathode mechanism for the replenishment of eroded cathode material, an anode pre-filter, a flat-shaped filter coil, a source-substrate filter separation wall, a magnetic multipole plasma homogenizer, a optimized plasma expander coil, an improved pulse-forming network, and the optimization of the "triggerless" or self-triggering principle. Overall, the features introduced led to several patent disclosures that were consolidated in three patent applications with the US Trademark and Patent Office.

3. The "alpha" version was extensively tested jointly by Berkeley Lab, Read-Rite, and CVC personnel. By the year 2000, the requirements for "ultrathin" films went from 7 nm at the beginning of the CRADA negotiations (1996/97) to 5 nm at the beginning of the CRADA work (1998) to 4 nm, or perhaps even 3 nm. It could be shown that one could deposit ultrathin films down to 3 nm with the "alpha tool," going beyond the original goal. Some experimental tests indicated that even 2 nm films are possible although theoretical arguments (as explained below) indicate that 2 nm is about the fundamental physical limit of synthesizing diamond-like carbon films.

4. The work at this CRADA was at the cutting edge of technology related to magnetic storage of information. The achievements were recognized by assigning *Invited Talks* at several international conferences, specifically:

- the International Conference on Metallurgical Coatings and Thin Films (ICMCTF, April 2000),
- the International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV, September 2000),
- the Symposium on Interface Tribology Towards 100 Gbit/in^2 and Beyond (October 2000)
- the Annual Meeting of the German Physical Society (DPG, March 2001)
- the Annual Spring Meeting of the Materials Research Society (MRS, April 2001)
- the European Vacuum Conference (EVC, September 2001).

5. This CRADA was not without "ups and downs" mainly caused by the volatile commercial environment. One manifestation is the fact the industry partner was acquired / merged twice during the short period of the three year duration of this CRADA. At the same time, the technical goal of making ultrathin continuous diamond-like carbon films changed in terms of thickness required for future magnetic storage devices. The storage density did not only double in the usual 18 months cycle ("Moor's law) but accelerated to a cycle of about 12 months, pushing the film requirements to even tighter limits and closer to the limits of physical feasibility. Additionally, due to fierce competition in this tight market, the profit margin for magnetic storage devices fell and is now very small or non-existent. Consumers can now buy hard disk drives for as little as $2 per Gbyte. As a result of this amazing development, funding for research and development is, ironically, increasingly harder to obtain. Equipment manufacturers such as CSC/CVC/Veeco feel first the result of reduced profit margins due to the reluctance of disk and magnetic head makers to invest in new deposition equipment. This development lead us, the CRADA partners, focus on demonstrating the feasibility for filtered arc coatings on magnetic heads while postponing the deposition on disks. With the change of industry structures, the goal of making an arc source compatible with a disk coater such as Intevac's MDC-250 was replaced with the strategic goal to reduce the thickness of the coating to less than 5 nm while still providing chemical and mechanical protection of the magnetic layers. This strategic decision was well founded on the technical level of the technology and demands of the markets.

4. Deliverables:

Deliverable Achieved	**Party (LBNL, Participant, Both)**	**Delivered to Other Party?**
Development of a laboratory prototype of a novel 3-dimensional macroparticle filter ("Twist Filter") (patent pending)	Berkeley Lab	
Studies of plasma transport and filter optimization	Berkeley Lab	
Development of novel cathodic arc plasma source that features an advancing cathode such as to replenish cathode material without breaking vacuum (part of a pending patent)	Berkeley Lab	
Development of a thyristor-switched pulse-forming network used as a matched power supply for self-triggered arcs (part of a pending patent)	Berkeley Lab	
Development of a magnetic multipole homogenizer used to obtain uniform films from a point-like plasma source	Berkeley Lab	

Development of a commercial "alpha" version of a Twist Filter system, comprising of ➢ Twist Filter ➢ Cathodic arc source with advancing cathode ➢ Switched pulse-forming network ➢ Plasma expander and homogenizer ➢ particle separator	both	delivered to Read-Rite, a customer of CSC/ CVC/ Veeco
Testing of commercial "alpha" tool at Read-Rite's clean room, using Read-Rite's substrates and testing procedures	both	
Improving film uniformity over 6 inch wafer by implementing an electromagnetic multipole homogenizer between the filter and substrate; perform simulations describing plasma distribution	both	
Write reports and publications, for details see point 5.	both	

5. Identify publications or presentations at conferences directly related to the CRADA

[1] A. Anders, "Approaches to rid cathodic arc plasma of macro- and nanoparticles: a review," Invited Talk at the International Conference on Metallurgical Coatings and Thin Films (ICMCTF, April 1999), published in *Surf. & Coat. Technol.*, vol. 120-121, pp. 319-330, 1999.

[2] A. Anders, R. A. MacGill, and T. A. McVeigh, "Efficient, compact power supply for repetitively pulsed, "triggerless" cathodic arcs," *Rev. Sci. Instrum.*, vol. 70, pp. 4532-4534, 1999.

[3] A. Anders and R. A. MacGill, "Twist Filter for the removal of macroparticles from cathodic arc plasmas," presented at the International Conference on Metallurgical Coatings and Thin Films (ICMCTF, April 2000), published in *Surf. & Coat. Technol.*, vol. 133-134, pp. 96-100, 2000.

[4] A. Anders, W. Fong, A. Kulkarni, F. R. Ryan, and C. S. Bhatia, "Ultrathin diamond-like carbon films deposited by filtered carbon vacuum arcs," Invited Talk presented at the International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV, September 2000), *IEEE Trans. Plasma Sci.*, vol. 29, no.5, in print, 2001.

[5] A. Anders, "Energetic deposition using filtered cathodic arc plasmas," Invited Talk *presented at 7th European Vacuum Conference, Madrid, Sept. 2001, to be published in VACUUM*, 2002.

[6] A. Anders and F. R. Ryan, "Ultrathin ta-C films on heads deposited by twist-filtered cathodic arc carbon deposition," Invited Talk presented at the Symposium on Interface Tribology Towards 100 Gbit/in^2 and Beyond, Seattle, WA, 2000.

[7] A. Anders and A. V. Kulkarni, "Synthesis of ultrathin ta-C films by twist-filtered cathodic arc carbon plasma (invited)," Invited Talk presented at Spring Meeting of the Materials Research Society, San Francisco, April 2001, published in *Proc. Mat. Res. Soc.*, in print, 2001.

[8] D. M. Sanders and A. Anders, "Review of Cathodic Arc Deposition Technology at the Start of the New Millennium," Invited Talk at the International Conference on Metallurgical Coatings and Thin Films (27th ICMCTF, San Diego, April 10-14, 2000), published in *Surf. & Coat. Technol.*, vol. 133-124, pp.78-90, 2000.

[9] T. Schülke and A. Anders, "Velocity distribution of carbon macroparticles generated by pulsed vacuum arcs," *Plasma Sources Sci. Technol.*, vol. 8, pp. 567-571, 1999.

[10] O. Monteiro and A. Anders, "Vacuum-arc-generated macroparticles in the nanometer range," *IEEE Trans. Plasma Sci.*, vol. 27, pp. 1030-1033, 1999.

[11] A. Anders, "Imaging the separation of cathodic arc plasma and macroparticles in curved magnetic filters," *IEEE Trans. of Plasma Sci.*, in print, 2001.
[12] A. Anders, "Chopping effect observed at cathodic arc initiation," *IEEE Trans. of Plasma Sci.*, vol. 28, pp. 1303-1304, 2000.
[13] M. M. M. Bilek and A. Anders, "Designing advanced filters for macroparticle removal from cathodic arc plasmas," *Plasma Sources Sci. Technol.*, vol. 8, pp. 488-493, 1999.
[14] M. M. M. Bilek, A. Anders, and I. G. Brown, "Magnetic system for producing uniform coatings using a filtered cathodic arc," *Plasma Sources Sci. Technol.*, vol. 10, in print, 2001.

6. List of Subject Inventions and software developed under the CRADA:

Disclosure or patent number	Title	Inventors and Affiliation	Date filed
IB-1484	Twist-Filter for Cleaning of Cathodic Arc Plasmas	A. Anders, R. MacGill, both LBNL	2-1-1999
IB-1497	Cathodic Arc Plasma Source	A. Anders, R. MacGill, both LBNL	
CIB-1563	Magnetic Expander and Homogenizer System for Filtered Cathodic Arc Plasmas	A. Anders, LABNL, and M. Bilek, Univ Cambridge	9-3-1999

A provisional patent application consolidating the above disclosures was filed with the US Trademark and Patent Office on 3/31/1999, followed by a regular application on year later. Patents are pending. For more information contact Henry Sartorio (510) 486-4534.

7. A final abstract suitable for public release:

(Very brief description of the project and accomplishments without inclusion of any proprietary information or protected CRADA information.)

Magnetic storage of information on hard disks and similar technology is based on the ability to precisely deposit multilayers of magnetic material sealed by an ultrathin protective layer. This protective layer is commonly a form of diamond-like carbon. In order to increase the storage density, the read-write head has to be extremely close to the layers that store the information. Therefore, the protective layers on disk and head have to be as thin as possible while still providing protection against corrosion and wear.

The Plasma Applications Group of Lawrence Berkeley National Laboratory has partnered with Commonwealth Scientific Corporation (CSC), later CVC/Veeco, to develop a novel deposition system capable of making protective diamond-like carbon layers that are thinner (5 nm, as of 1997) than layers made by conventional technology (7 nm as of 1997) while still meeting protection requirements.

Filtered cathodic arc plasma deposition was identified as a promising technique provided the issue macroparticle removal could be solved. A novel filter system, the Twist Filter, was invented, produced, and tested. The Twist filter shows superior filter capabilities and improved plasma transport compared to previous devices. One system was installed at a leading read-write head manufacturer. Extensive tests have shown that films as thin as 3 nm can be made efficiently and reliably and

reproducibly, meeting the stringent requirements of the industry. Tests further indicate that even thinner films may be possible, approaching the physical feasibility limits of diamond-like films. Further engineering efforts are needed to develop the system into a commercial deposition tool.

The CRADA has resulted in several invention disclosures leading to three patent applications. The work was published in 14 publications, 5 of which were Invited Talks at National and International Conferences.

8. Benefits to DOE, LBNL, Participant and/or the U.S. economy.

Cathodic arc plasma are unique in that they are fully ionized contain energetic, often multiply charged ions. The utilization of such plasmas for surface engineering is still in its infant stage due to severe drawbacks caused by the presence of "macroparticles", i.e. micron-size cathode droplets and debris particles. Managing this issue could have important implications for a number of high-tech industries, national defense industry, as well as basic science. This CRADA work demonstrated that ultrathin (3 nm thick) diamond-like carbon films can be made using improved filtered arc technology. The films made were shown to be superior to films made by conventional deposition techniques such as sputtering or ion beam deposition.

The benefits to DOE and Berkeley Lab are several. First, the department and the lab have advanced the basic understanding of cathodic arc plasma production, plasma transport, plasma-surface interaction, and film formation. Second, the department has demonstrated the capability of synthesizing superior films such as diamond-like films that could be applied to a number of applications, including wear and corrosion protection, and as optical films. Third, the results achieved with this CRADA work are an excellent basis for expanding deposition research with filtered arc plasmas – the department and the lab could maintain the position of a leader of research and development in this field.

The five Invited Talks are a clear sign that the community regards this work as leading. The participants have a competitive advantage which is, however, only short-lived in this very dynamic environment. Further research and development must follow quickly to maintain this advantage. One proof of how dynamic this field is the fact that the initial CRADA negotiations anticipated 7 nm thick films, a goal that to had to be corrected to 5 nm by 1998 and to 3 nm by 2000.

The benefit to the industry participant and the U.S. economy is to have developed a candidate process of producing ultrathin protective layers for future magnetic storage devices. The results achieved are the best in the industry if compared with competing technologies. However, one has to recognize that filtered arc technology is commercially not as mature as other technologies that have been used for decades. With the recent industrial downturn and practically non-existing profit margins in the magnetic storage industry, further investments in this technology are likely to occur in areas other than the storage industry, e.g. in the optical communications industry and in MEMS (micro electromechanical systems).

9. Financial Contributions to the CRADA:

DOE Funding to LBNL	k$ 750.0
Participant Funding to LBNL	k$ 265.4
Participant In-Kind Contribution Value	k$ 750.0
Total of all Contributions	k$ 1765.4

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