Transfer of an Evolving Technology

by

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Submitted to the Sloan School of Management and
the Department of Chemical Engineering
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Abstract

This thesis follows the transfer of a thin film from development to manufacturing. Problems of differences in equipment and differences in manufacturing methods were overcome to complete the transfer. The film was characterized using UV-Visible, FTIR, and Raman spectroscopy. Hydrogen forward scattering, surface bead angle, and atomic force microscopy were also employed. A series of experiments was conducted to:

1) Analyze the impact of deposition parameters on the performance of the film.
2) Match the performance of films produced in the manufacturing site to the performance of films produced in the development site.

Both the development and manufacturing sites were acquired by a new company during the period of this transfer. The cultures of the development and manufacturing sites had not merged before this occurred. This fact, coupled with subsequent reorganization undertaken by the new management, has the potential to slow product introductions.

The transfer of this film was successful despite the organizational upheaval occurring at the same time. Three factors contributed to this success:

1) The development engineer stayed with the process throughout the transfer to manufacturing.
2) The collaboration of upstream manufacturing steps integrated the new process with the existing line.
3) Early involvement of manufacturing speeded acceptance and lessened training costs.

Recommendations to better link the manufacturing and technology development groups, based on observations made during work on the film transfer, are presented for management's consideration. Key among these is the establishment of common goals and the building of a communication infrastructure between the two sites.

Thesis Advisors:
Professor Michael Cima; Department of Materials Science and Engineering
Professor Klavs Jensen; Department of Chemical Engineering

Acknowledgments

Hundreds of people contributed to the process transfer described in this thesis. It would be impossible to list them all, but a few stand out. John Berg, Jim Getz, and Francis Campos provided excellent guidance. I learned much from each. Hong Li was instrumental in getting the friction testing done. Mitch Szymanski helped with the breakdown tests and Marcia Misiorski helped with the AFM. A special thanks goes to Brian Cumpston for his help with the FTIR. Jim Remby provided the upstream process support.

This research was conducted through the Leaders for Manufacturing Program; a partnership between MIT and US manufacturing firms. One of those firms, Intel Corporation, sponsored my participation in the Leaders for Manufacturing Program. I am grateful for the company's support. David Marsing, Mike McKinney, and Steve Thompson deserve much of the credit for my attendance.

My advisors, Michael Cima and Klavs Jensen, and my reader, Don Rosenfield, were outstanding. Through their visits, friendly cajolery, personal libraries, and investment of time, they contributed much to improve this effort.

Table of Contents

Introduction

This thesis follows the transfer of a friction-reducing thin film from development into manufacturing. Two problems are encountered. The first problem is that of transferring a technology that is still evolving. In particular, a different vendor's equipment is used to manufacture the film than was used to develop it. The work involved understanding the differences in the equipment and understanding the interaction between the equipment and the film it produced. The second problem springs from cultural differences between the development and manufacturing sites. The development site had been acquired by the manufacturing company for their technology. Cultural differences between the sites were large, and slowed the rate of technology transfer. In the middle of the transfer, a third company bought both units, compounding the changes already underway. The evolution of the technology interacts with the evolution of the cultures.

The first section of this thesis is a brief review of disk drive market forces and technology. This is presented to put the thin film in context. The second section describes the metrology used to measure the film. The third, fourth and fifth sections describe three experiments used to:

1) Explore the impact of deposition parameters on drive performance
2) Match one sputtering system to the other
3) Look at the question of how thin the film can be and still be effective

A discussion of the experiments follows these sections.

The thesis next moves from exploring the film to exploring the organizations involved. It documents the interaction of this process step with the rest of the line. It discusses how manufacturing was involved with the new process and the essential role the development engineer played in the transfer.

A description of the impact of the takeovers and recommendations to the new company concludes the thesis.

Technology Climate

Hard drives manufacturers compete in a market tightly coupled to the electronic revolution. The rate of technological change is comparable to that in the semiconductor industry. Among many market forces, there is an ever-increasing demand for data storage. Notebook computers must have small, light, power-conserving mechanisms. Customers are demanding greater drive reliability. Each of these will be discussed in turn:

More storage will be required

Storage needs keep increasing. The versions of Microsoft Word™ and Microsoft Excel™ used in 1984 took less than one megabyte of hard drive storage apiece. The latest versions -- with all their built in help, grammar checking, advanced statistical functions, and cross-program linking -- use an incredible 25 megabytes each. That's a 2500% increase in 10 years or a growth rate of 38% per year. There has been little pressure to reduce code volume. Consumers value features more than parsimony of storage. Storage technology has kept pace with the growth of programs. Programs thus continue to grow.

A second factor fueling the growth in required storage is the move toward digital video. One picture may be worth a thousand words, but it takes up ten thousand times the number of bits. At 30 frames a second, drives fill up rapidly. A 135 minute movie takes up 3700 Megabytes of storage[1].

Between the growth of programs and the desire to store lots of pictures, demands on storage are likely to accelerate. Electronic Design magazine reports that the doubling period of hard drive capacity is 18 months [2]. This is an astonishing 58% per year growth rate.

Notebook computers require energy and size efficiency:

Portable computers are the fastest growing segment of the computer market, and they account for about one-fifth of all computers sold[3]. Because they are battery powered, they must be much more energy efficient than desktop machines. Because they are carried about, size and weight are important selling points. Few people, though, are willing to give up storage space in their portable computer. Even the minimum installation of Microsoft Word requires ten megabytes of hard drive space. Physical size and power consumption have become important hard drive parameters.

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[1] Trachtenberg, Jeffery; "Sony Alliance with Philips Faces Threat"; The Wall Street Journal; January 23, 1995; A3.

[2] Nass, Richard; "Hard Disk Drives Pack More Data Into Less Space"; Electronic Design; 41:9; May 3, 1993.

[3] Taylor, Paul; "Tumbling Prices Ignite Market"; Financial Times; October 26, 1994.

Power consumption has moved beyond the notebook market
The three largest power users in any PC are the monitor, the CPU and the hard drive. Since the government "Energy Star" program debuted in 1993, desktop PCs have become energy-conscious. To get an energy star rating (and thus be considered for purchase by a government agency and many other large firms), a PC must automatically go into an idle mode in which it draws less than 30 watts of power. The most common adaptations made to get an Energy Star rating are to:

1) Turn the monitor down or off
2) Put the CPU into a standby condition
3) Stop spinning the hard drive disk

This last is of particular concern to the hard drive manufacturer, because it interacts with drive reliability.

Access times must be faster.
Hard drive access times have to keep pace with the advent of ever-faster CPUs. This is often encountered when upgrading the CPU on an older computer. The full benefit of a faster CPU can be clipped by a slow drive.

Consumers are demanding more for less
As drives hold more and more data, and as people integrate computers more and more into the fabric of their lives, drive crashes become more catastrophic. As with many goods, reliability is becoming more and more critical. Fifty percent of PCs sold now go to home use[4], and people compare the reliability of their computer with the reliability of their television set. The drive industry has increased the performance/price ratio so consistently that consumers now expect to pay less per megabyte as time passes.

In summary, the direction for hard drive evolution is:

1) Larger capacity
2) Physically smaller
3) Weighs less
4) Consumes less power
5) Faster access times
6) More reliable
7) Costs less

Magnetic Hard Drive Overview
The basic hard drive consists of a disk coated with magnetic material spinning underneath a small electromagnet mounted on a bit of ceramic. The electromagnet and ceramic together are called the read-write head. This head is supported just above the disk surface. The support is provided by an arm that cantilevers the head out over the disk. A typical head and support arm is pictured in Figure 1. A drive is comprised of this assembly and a disk, housed together with power supplies and integrated circuits that manage the flow of information to and from the disk.

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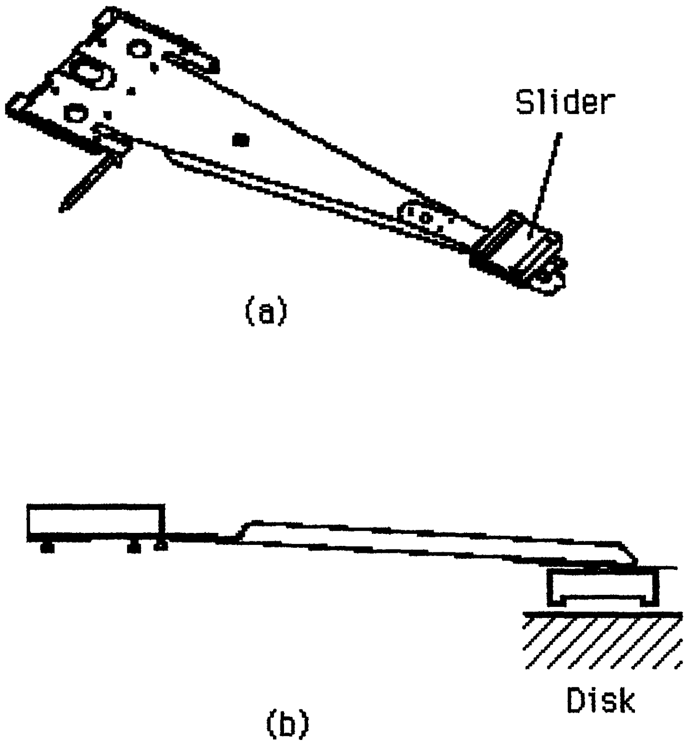
[4] Webster, Guy; "Intel targets growing home market"; The Arizona Republic; April 24 1994; H4.

Figure 1[5]: (a) the side of the head and suspension that faces the disk. (b) how the suspension supports the head above the disk.



It looks, and moves, something like a vinyl phonograph album, arm and needle. Only the disk is spinning at 3000 to 5000 rpm, and the head is not confined to grooves in the disk. The head actually flies in the boundary layer of air above the spinning disk, and can move radially as the need to imprint or retrieve information dictates. When the disk stops, the air motion which allows the head to fly ceases, and it lands on the disk.

The ceramic portion of the read-write head has a variety of names. It is sometimes called an air bearing and is sometimes called a slider. The term air bearing comes from the flying characteristics of the head. The term slider is a historical holdover from the time when the recording head slid along the surface of the disk rather than flying above it.

Many of the hard drive market demands complement one another
It is easy to understand that a smaller drive is apt to be lighter, and is apt to consume less power. Access times will be improved because the read-write head will not have to travel as far to get to where it needs to be over the disk.

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[5] Bhushan, Bharat; Tribology and Mechanics of Magnetic Storage Devices; Springer--Verlag; 1990; p 29.

Some demands are contradictory

A smaller drive, all other things equal, can not hold as much data as a larger unit. Manufacturers have had to compress data into smaller spaces, thereby increasing the density of data on the disk. Bits of data are smaller in area and are packed closer together. This is called the areal density of a drive. Its units are megabits per square inch. The areal density of drives has increased as technology has improved. Today's drives run about 350 megabits per square inch. Today's most common technology -- an inductive magnet both reads and writes -- is forecasted to suffice to about 500 megabits per square inch. Market forecasts see the need for gigabit per square inch drives within the next five years. This is thought to require different technology. A favored new technology pairs a magneto-resistive (MR) read element and an inductive write element. This solves the problem of inductive heads writing more finely than they can read. Magneto-resistive heads have demonstrated gigabit/square inch performance in the laboratory.[6] Conceptual diagrams of inductive and MR heads are shown in Figures 2 and 3. A cutaway drawing of an actual inductive element mounted on a slider next to a disk is shown in Figure 4. Because it senses a change rather than an absolute, an MR element is more easily miniaturized than an inductive element. The improved performance isn't free. The MR device only reads; an inductive write head is still required. The MR element also requires sensitive biasing and measurement circuitry.[7] The manufacturing process is longer and more expensive because of the added complexity.

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[6] Nass, Richard; "Hard Disk Drives Pack More Data Into Less Space"; Electronic Design; 41:9; May 3, 1993.

[7] Bhushan, Bharat; Tribology and Mechanics of Magnetic Storage Devices; Springer--Verlag; 1990; p 40.

Figure 2: **An inductive head is based on an electromagnet**

Apply current to write to the disk or measure voltage to read from the disk. The same element both reads and writes.

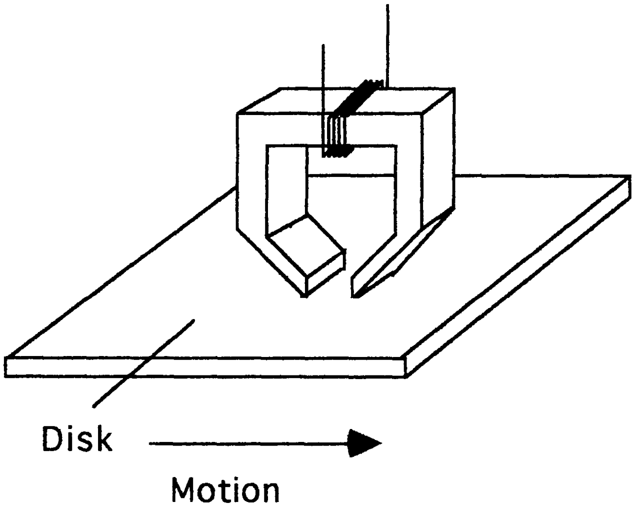


Figure 3: **A Magneto-Resistive Read Head**

The MR head is based on the change in resistance of a magnet in the presence of magnetic flux. This head can only read. An inductive head is typically used to write.

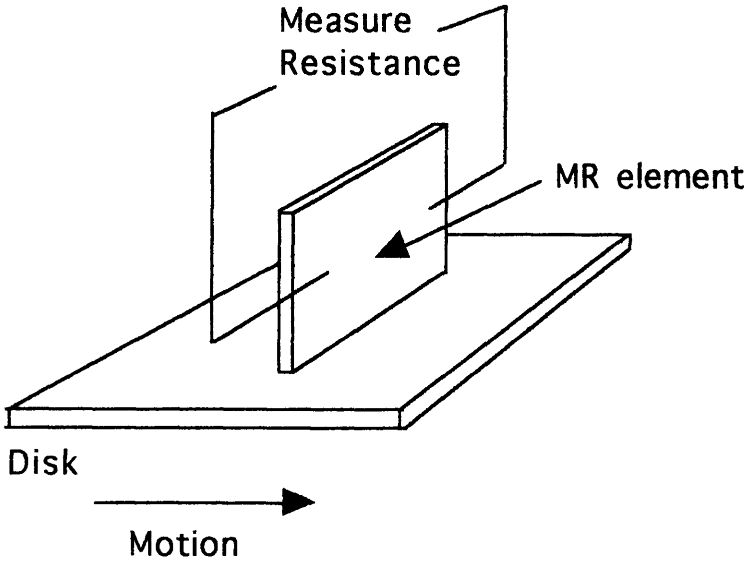
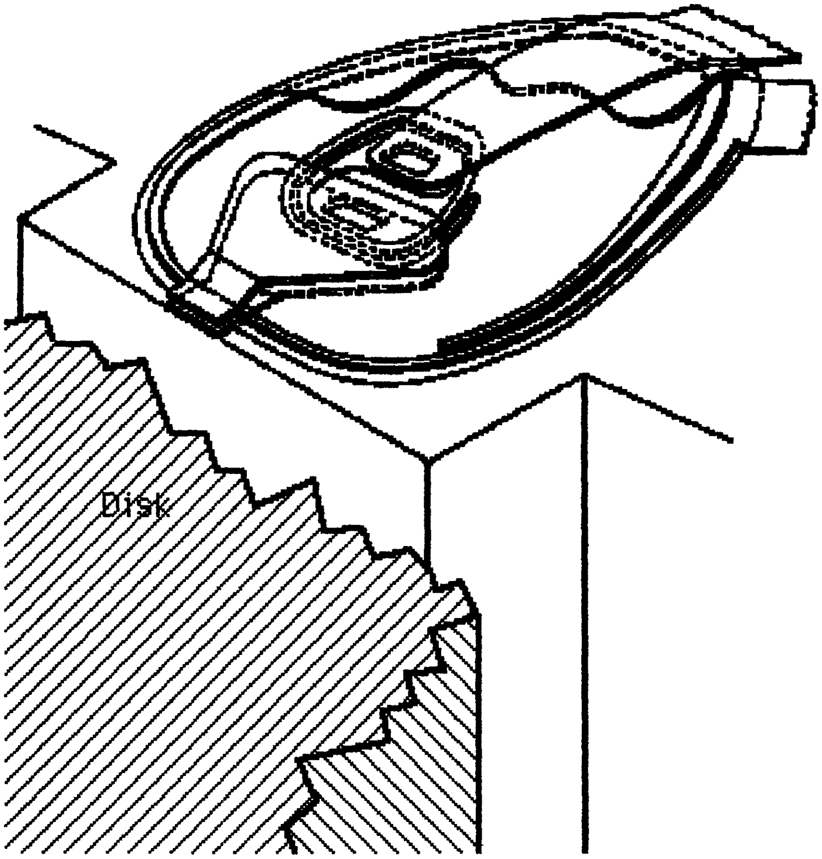


Figure 4[8]: Cutaway drawing of inductive element mounted on a slider



Another way to achieve greater areal density is to move the recording head closer to the recording media. This works with both inductive and MR heads. Decreasing the space between the magnet and the disk increases the magnetic flux and allows everything to be made smaller. Smaller means faster. Today's heads fly two to four microinches (one microinch = 10^{-6} inch = 254 angstroms) above the disk. Comparing the head dimension to that of an aircraft, one finds that this is equivalent to a Boeing 747 flying 1/10 of an inch off the ground and circling the Earth in three minutes.

Some vendors have drives incorporating heads which can be thought of as "tail draggers". The bulk of the head is flying, but the section containing the electronics is actually dragging along the surface of the disk.

The trade-off in decreasing the head flying height is in drive reliability. The closer the head flies to the disk, the more often they collide. The more often they collide, the sooner the drive fails. As the head to disk spacing has decreased, more protective and lubricating layers have been applied between the two to improve drive longevity.

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[8] Bhushan, Bharat; Tribology and Mechanics of Magnetic Storage Devices; Springer--Verlag; 1990; p 28.

In addition to collisions, the head and the disk come into contact each time the disk stops spinning. Remember that a common method of achieving low power operation is to spin-down the drive. When the disk is spun down, the head lands on an area of the disk set aside for that purpose. Even though it has a dedicated landing strip (circle), the head comes into contact with the drive and wear occurs. Eventually either the head is damaged such that it can no longer fly, or the electromagnet is damaged such that it can no longer read and write. Manufacturers desire to postpone these events as long as possible. Marketplace demands have made this more difficult. The lower fly heights brought about by increasing areal densities and the increased number of spin-ups and spin-downs brought about by power conservation have put added stress on the interface between the head and the disk. The tribology of this contact area, called the Head Disk Interface, is key to drive reliability.

The Head Disk Interface:

The Head Disk interface has evolved over time. Early drives (Figure 5) used ceramic heads and disks coated with magnetic material. The magnetic material was easily damaged by the head. In the 1980's a protective coating was added to the disk (Figure 6). The industry settled on amorphous carbon or amorphous hydrogenated carbon as the protective coating of choice. Sometimes these amorphous carbon and amorphous hydrogenated carbon films are called "Diamond-Like-Carbon" or DLC, because they can approach some of the physical properties of diamond. Hard carbon films increase the wear performance of the head-disk system by a factor of six[9]. The physical properties and tribological performance of these films have been the focus of hundreds of papers from the early 1980s to the present. Ager[10], Agarwal[11], Bhushan[12], Ganapathi[13], Lauer[14], Lee[15], Marchon[16], Tsai[17], and Yoshikawa[18] are a few of the more prolific researchers.

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[9] Agarwal A.K., Shih, C.Y., Harper, M.A., and Bauer, C.L.; "Effect of surface coatings on sliding friction and wear of thin -film magnetic recording media"; Tribology and Mechanics of Magnetic Storage Systems; VI; B. Bhushan and NS Eiss, Jr. Eds; STLE SP-26; 1989; p 8.

[10] Ager, Joel, III; "Optical Characterization of Sputtered Carbon Films"; IEEE Trans Magnetics; 29 (1); 1-93; 259.

[11] Agarwal, S. and Li, E.; Structure and Tibological Performance of Carbon Overlayer Films; IEEE Transactions on Magnetics Vol 29:1; Jan 1993.

[12] Bhushan, B. and Ruan, J.A.; Atomic scale friction measurements using friction force microscopy: Application to magnetic media; ASME Journal of Tribology; Vol 116, Issue 2; 1994.

[13] Ganapathi, S.K., Talke, F.E. and Balanson, R.D.; "Correlation between Contact Start Stop and Constant Speed Drag Testing in Magnetic Head-Disk Tribology"; ASME Journal of Tribology; 33; 1993.

[14] Lauer, J.L. and DuPlessis, L.; "Relationship between deposition parameters, structure and raman spectra of carbon overcoats on simulated magnetic storage discs"; Tribology Transactions; Vol 36, Issue 1; 1993.

[15] Lee, J.K., Smallen M., Enguero, J., Lee, H.J. and Chao A.; The Effect of Chemical and Surface Properties of H: Carbon overcoats on the Tribological Performance of Rigid Disk Media; IEEE Trans. Magn. 29:1 (1993).

[16] Marchon, B., Heiman N., and Khan M.R.; "Evidence for tribochemical wear on amorphous carbon thin films"; IEEE Trans Mag; 26 (1); 1-90.

[17] Tsai, H., Bogy, D.B., Kundmann, M.K., Veirs, D.K., Hilton, M.R., and Mayer, S.T.; "Structure and properties of sputtered carbon overcoats on rigid magnetic media disks"; J. of Vac. Sci. Technology A; 6 (4); 7-88.

[18] Yoshikawa, M., Katagiri, G., Ishida, H., Ishitani, A.; "Raman spectra of diamondlike amorphous carbon films"; J Appl. Phys.; 64 (11); 12-88.

Figure 5: Early drives had no protective coating on the disk

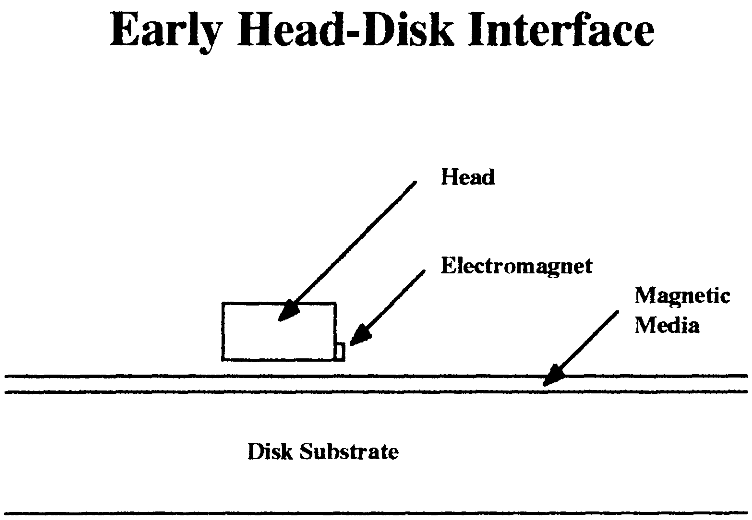
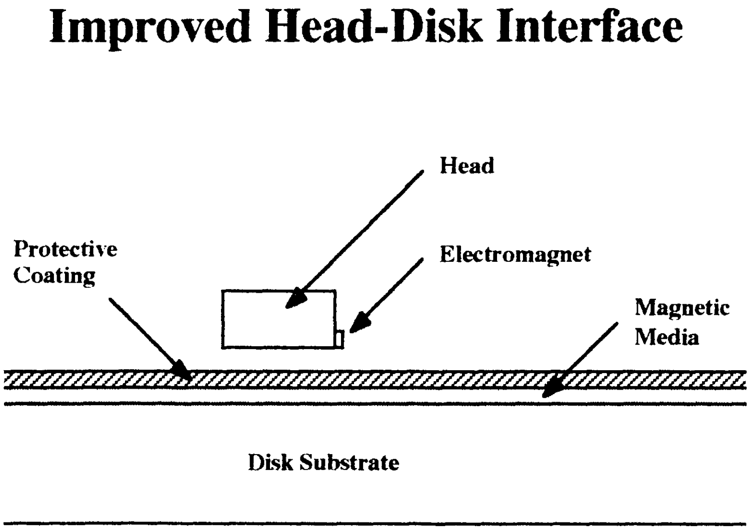


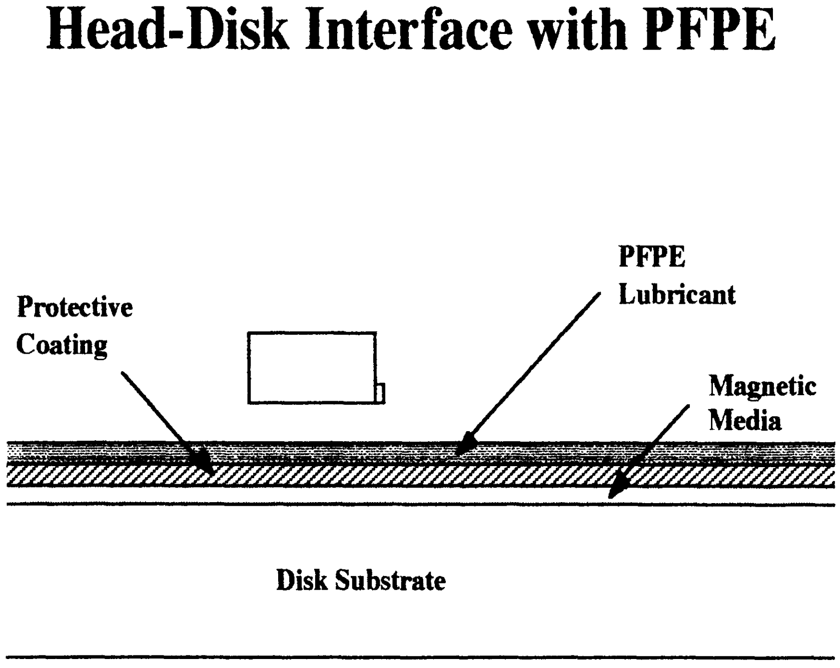
Figure 6: A protective hard carbon disk coating was added in the early 1980s



A review of this literature suggests that there are many factors contributing to the tribology of the head disk interface. Among them are the surface roughness of the disk, the thickness of the protective films, the atomic structure and stoichiometry of the materials involved, the shape of the head, the number and type of particulates in the drive, and the ambient surrounding the head and the disk. Oxygen has been shown to reduce drive lifetimes. Humidity can increase the static and dynamic friction between the head and the slider.

One result of this growing understanding is that some disk manufacturers have augmented the protective properties of the carbon film by adding a perflouropolyether (PFPE) as a second coating on top of the amorphous carbon layer (Figure 7). This oil increases the reliability of the system by a factor of ten[19]. One explanation for this is that the oil displaces water from the disk surface[20,21].

Figure 7: **A PFPE lubricant was added to the Head-Disk Interface**



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[19] Chu, M., Bhushan, B., and DeJohghe, L.C.; "Wear behavior of ceramic sliders in sliding contact with rigid magnetic thin film disks"; Tribology Transactions; Vol 35 Issue 4; 1992.

[20] Chen, Xuan; "The Effect of Lubricant Roughness Ratio, Lambda on Tribological Performance of Magnetic Thin Film Disks"; IEEE Transactions on Magnetics; Vol 29 (6); 1993.

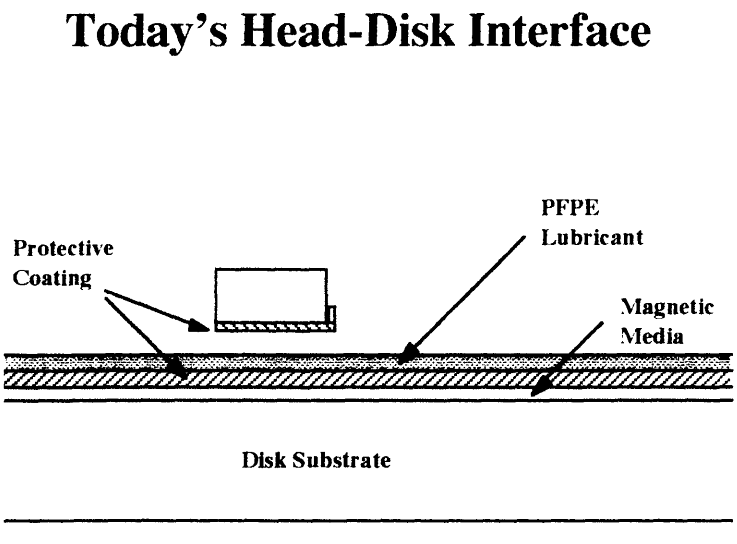
[21] Li, Y. and Talke, F.E.; "A model for the effect of humidity on stiction of the head/disk interface"; Tribology Transactions; Vol 35, Issue 3; 1992.

The most recent stage in the head disk interface evolution has been the addition of a protective coating on the bottom of the head (Figure 8). This protective coating lowers the static and dynamic friction between the head and the disk. This lower friction reduces disk wear. A second benefit is that the protective coating slows the Al_2O_3 catalyzed breakdown of commonly used PFPEs[22]. The addition of the coating has two disadvantages. One, it increases the cost of head manufacture. Two, it increases the spacing between the read-write circuitry and the disk by an amount equal to the film thickness.[23]

This thesis describes the transfer of a tri-layer[24] head coating from a technology development site to a high volume manufacturing facility. The three layers, from the slider Al_2O_3-TiC ceramic out, are:

Silicon -- for adhesion
Carbon
Silicon

Figure 8: The topic of this thesis is the protective film on the bottom of the head



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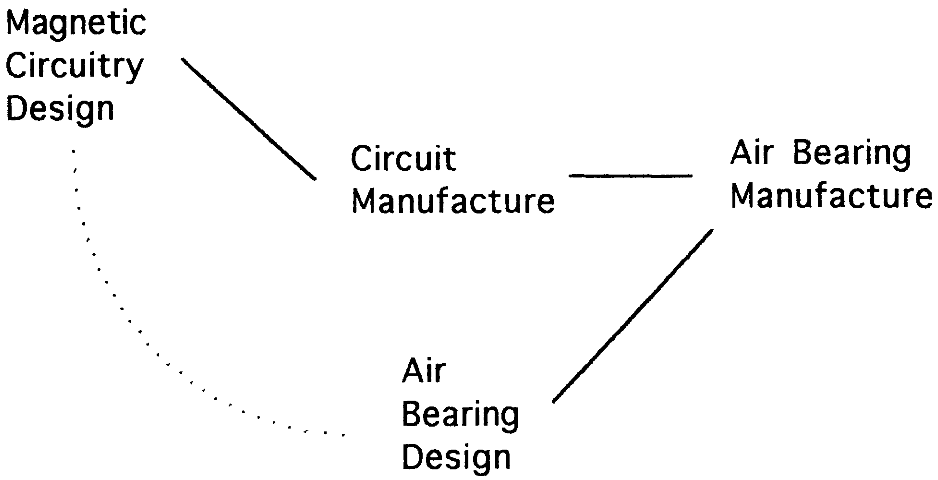
[22] Kasai, P.H.; "Degradation of PFPEs catalyzed by Lewis Acids"; Adv. Info. Storage Syst. ; Vol 4; 1992.

[23] Bhushan, B.; "Magnetic Slider/Rigid Disk "Substrate materials and Disk Texturing Techniques -- Status and Future Outlook"; Adv. Info. Storage Systems Vol 5; 1993; 175

[24] US Patent # 5,175,658; IBM; "Thin film magnetic head having a protective coating and method for making same"; 1992.

The data in this thesis concerns the Air Bearing portion of the recording head process
A simplified process flow for making recording heads is shown below:



The design of the circuitry and the design of the air bearing are only loosely coupled. The circuitry is manufactured in a wafer fabrication process similar to that used in the semiconductor industry, and the air bearings are then carved out of the substrate the circuitry was built upon. A variety of magnetic circuitry can ride on any given air bearing. The data and opinions in this thesis stem from the researcher's seven months of experience in the air bearing portion of the manufacturing line.

The first section of this thesis documented some of the market forces in the disk drive industry and showed how the technology has evolved to include a protective coating on the bottom of the head. The film has been placed in its technological and process context. Before proceeding with the particulars of film measurement, a few paragraphs are devoted to describing the status of the film-producing process in the development site at the time this thesis work began.

The film was well established in the development site at the beginning of the project
The film was running successfully in low volumes at the factory where it was developed. The engineer who had developed the process continued to support the process in manufacturing after development was complete. One year after the film was developed, transfer to a second, larger, and distant manufacturing site began.

Only two operators ran the operation through much of the first year in the development site. It was staffed for ten eight-hour shifts each week. Volumes were 10% to 20% of what the machine could support. Most of the operators' time was devoted to inspecting parts, precleaning parts, and manually loading parts into the sputtering system. This pre-run and post-run work consumed 2/3 of the total cycle time. The development deposition system requires manual sequencing that added to the operator workload. An operator must be present at certain points throughout the 45 minute cycle to initiate events in the sequence.

The process was very stable. The sputtering system had never constrained output despite being a single piece of equipment. No changes had been made to the process during the year it had been in production.

Choice of equipment in the receiving factory:

The receiving factory had several MAN® sputtering systems supporting other steps in the head manufacturing process. The factory was pleased with the process performance and the uptime of these machines. No DEV® sputtering systems like the development machine were used in the manufacturing factory. DEV systems were no longer produced. The vendor had discontinued the entire DEV line. Such systems could only be acquired on the used and refurbished market.

Because the receiving site desired an automated system, and because they already had solid maintenance expertise with MAN systems, the receiving factory proposed a MAN system. The engineer in the development site supported the proposal. The receiving factory purchased a MAN system, and the stage for the process transfer was set.

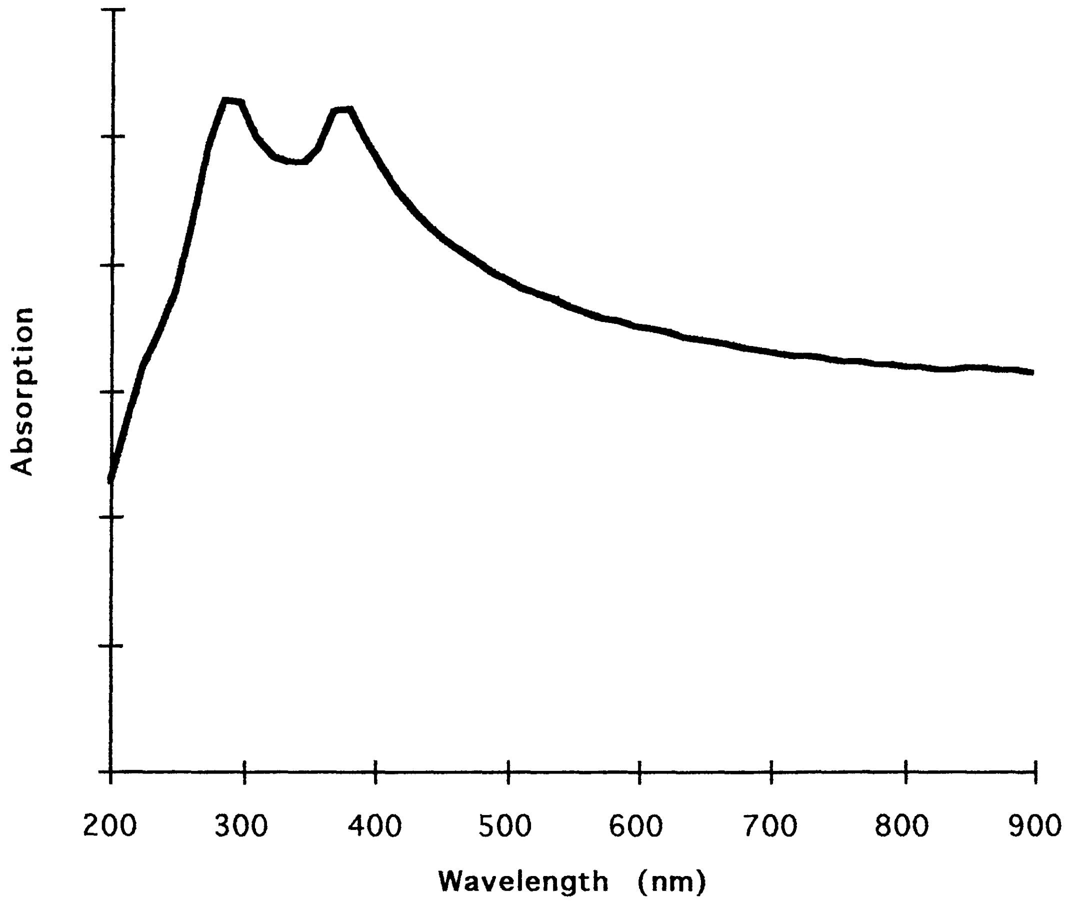
Metrology

The films produced during the course of this thesis were measured using the following tools:

UV-Visible optical analyzer

This tool is based on an industry standard UV-Visible spectrophotometer. It acquires scans from a film deposited on a single-crystal silicon substrate. The sample beam is referenced to a split passing through atmosphere. The scan covers the region of 200 to 900 nm. A typical absorption pattern is shown in Figure 9. This output is analyzed using a proprietary algorithm developed by Forouhi and Bloomer[25,26] with the result being the n and k fingerprint of the film (Figure 10). From this is extracted the film thickness and the film optical band gap.

Figure 9: Representative absorption trace from UV-Visible spectrometer



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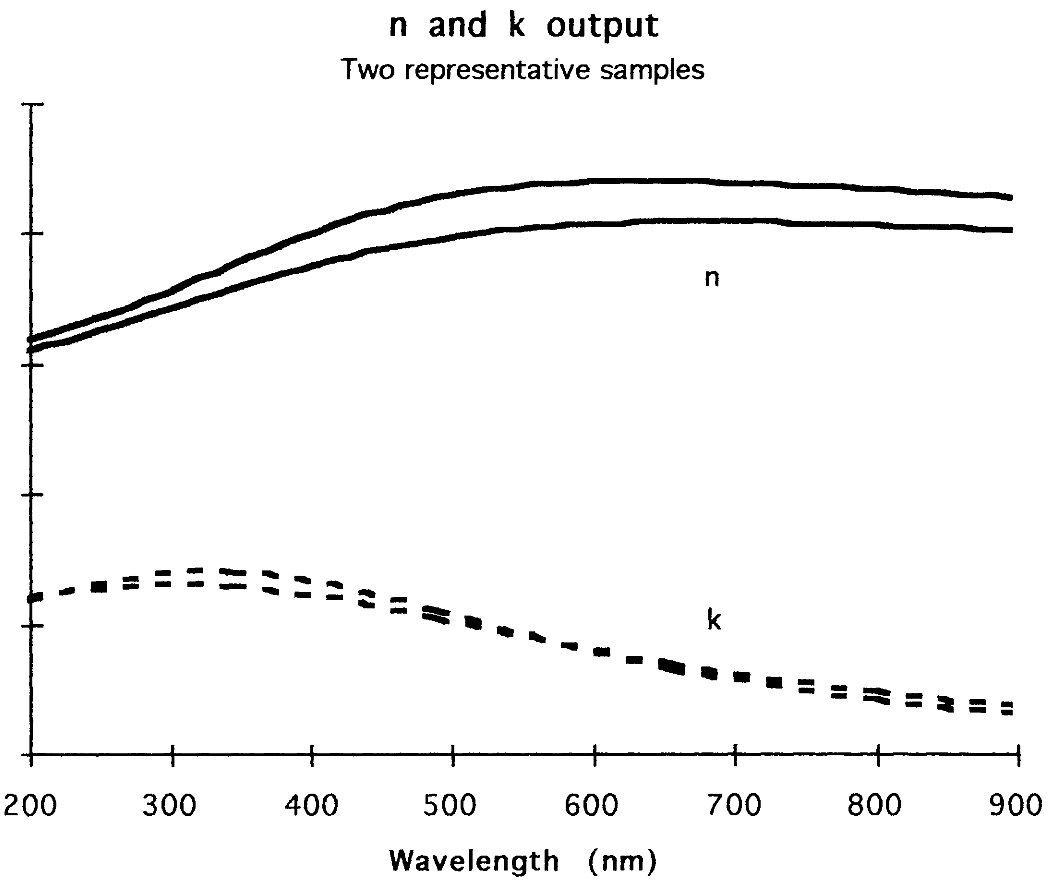
[25] Forouhi, A.R. and Bloomer, I.; "Optical dispersion relations for amorphous semiconductors and amorphous dielectrics"; Physical Review B; 34(10); 11-86.

[26] Forouhi, A.R. and Bloomer, I.; "Optical properties of crystalline semiconductors and dielectrics"; Physical Review B; 38(3); 7-88.

Figure 10: Representative n &k output



Thickness: The thickness indication thus produced was correlated to NBS standards through comparisons with an optical interferometer, and through comparisons with surface profilometers. The results matched within the measurement noise of the instruments.

Band gap: The band gap of a pure diamond crystal is 5.1 eV. The band gap of graphite is 0 eV. In graphite there is no separation between the valence and conduction bands. The optical band gap is defined as the wavelength whose energy corresponds to the gap between the valence and conduction bands of the amorphous material. The adsorption of these films has been shown to fit the model[27]

$$\omega^2 \varepsilon_2(\omega) = B\left(\hbar\omega - E_{opt}\right)^2$$

$$\varepsilon_2 = 2nk$$

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[27] Tsai, H. and Bogy, D.B.; "Critical Review -- Characterization of diamondlike carbon films and their application as overcoats on thin film media for magnetic recording"; J of Vac Sci A; 5 (6); 11-87

Amorphous hydrogenated carbon films have been found to be microcrystallites of sp^2 bonded carbon interlocked with bridges of sp^3 bonded carbons[28]. In these films, the optical gap has been correlated to the size of the sp^2 domains. The larger the sp^2 domains, the more sp^2 character to the film, and the lower the optical gap.

The UV-Visible system is not without its problems. There are four. First, the algorithm used to translate absorbance spectra into n, k, thickness, and Eg values is only valid for the range of film characteristics over which it has been calibrated. It has only been calibrated in a narrow range about the standard film. Films far from primary operating point show increasing deviations from the other tools. Calibrating over larger ranges requires preparing samples with known characteristics and gaining the involvement of the manufacturer to reprogram the algorithm. Second, at points within the operating range the system exhibits a bimodality. This is troubling to manufacturing personnel trying to control the deposition. Third, the system is very sensitive to minute changes in the angle of incidence of the beam. Fourth, cross-site comparison of the development UV-Vis and the manufacturing UV-Vis showed that the UV-Vis in the development site has a 10% offset in both thickness and Eg from the UV-Vis in the manufacturing site. The vendor has been unable to correct this problem.

Despite these drawbacks, the tool has emerged as the preferred method of immediate film feedback.

Raman Spectroscopy

This technique is documented in the literature as a method of measuring the amorphous hydrogenated carbon films used as disk coatings.[29] A high fraction of recent papers published on carbon films incorporate Raman spectra in their analysis. The films in this study were analyzed at an independent laboratory. An argon ion laser was used with a wavelength of 514 nm. The energy was 50 mW, which translates to an estimated 1 to 2 mW at the sample. Two factors compromised our Raman results. 1) The films exhibited a high fluorescent background which obscured much of the signal of interest. 2) Perhaps because of (1), the lab was not able to get a signal on our thinner samples. Thin samples comprised the bulk of our investigation. So the Raman work presented here is limited to three thicker samples.

Fourier Transform Infrared Spectroscopy

A Nicolet® 800 series IR system was employed. The sample was cleaved into two identical samples which were positioned around a KRS-5 (ThBr and ThI; 42/58%; n=2.38) crystal to provide total internal reflection. A DTGS-A detector was used. DTGS stands for dueterated triglycerine sulfate; the detector is pyroelectric. 512 scans were acquired which gave a collection time of approximately 40 minutes per sample. Sampling was randomized and was completed in one day of continuous FTIR operation.

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[28] Robertson, J.; "Mechanical Properties and Coordinations of Amorphous Carbons"; Physical Review Letters; Vol 68 (2); 1992.

[29] Ager, Joel, III; Optical Characterization of Sputtered Carbon Films; IEEE Trans Magnetics; 29 (1); 1-93; 259

Hydrogen Forward Scattering

The 2.1 Megavolt accelerator at Harvard was employed to examine the hydrogen content of the films. Accelerated helium ions knock the lighter hydrogen atoms forward out of the film and into a detector. The setup used was close to that described in Feldman and Mayer[30]. No calibrated standard was prepared for use with the samples. The output is thus suited only for qualitative, relative film comparisons. Since other measures (see discussion) provide an indication of the absolute hydrogen content this is not a drawback.

Goniometer

A goniometer was employed to study the deionized water bead angle behavior of samples. Provided the samples were fresh from deposition, the goniometer proved to be a sensitive indicator of deposition conditions. This matches the experience of Lee and Smallen[31]. The tool was more sensitive to changes than was the Eg output of the UV-Visible. Because the measurement is sensitive to technique (although the techniques are not difficult), it may not be suitable for production monitoring.

Low RPM Drag Tests

To measure the friction (dynamic friction) and stiction (static friction) between the coated head and the disk, a low rpm drag test was used. In this test, a head is set up over a disk. The head and disk surfaces are identical to those going into fully functioning drives. The disk is turned at one revolution per second, a speed which is below the takeoff velocity of the head. The head remains in sliding contact with the disk throughout the test. The gram-load on the head is known; the torque on the disk spindle is measured; thus the friction can be calculated. Due to time and equipment constraints, the drag tests in this study were limited to 24 hours. This represents only a fraction of the system's expected life under these conditions. Full tests typically run for two weeks or more. Due to the time constraints on this work and the number of samples required to overcome sample to sample variation, the shorter duration was a compromise made to expedite data collection.

Periodically through the drag test, the disk is stopped, allowed to rest for five minutes, and started again to measure the static friction at the head-disk interface. This static friction is higher than the dynamic friction. It sets a lower limit on the torque required from the disk motor.

The plots produced during the friction test look like the example in Figure 11.
A data point is collected every minute for 24 hours. The graph shows the increase and variance in the low rpm sliding friction at the head disk interface. Regression techniques were used to determine which sputtering parameters impacted friction. The average beginning friction, average friction at 24 hours and the time of the friction peak were examined.

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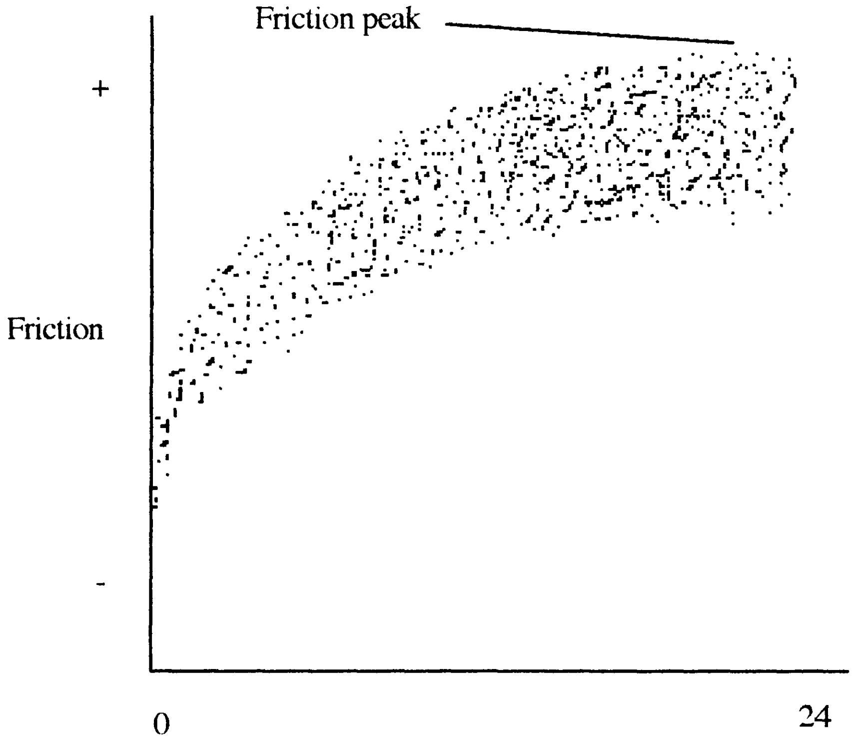
[30] Feldman, Leonard, and Meyer, James; Fundamentals of surface and thin film analysis; North Holland, New York; 1986; p 31.

[31] Lee, J. K., Smallen M., Enguero, J., Lee, H.J. and Chao A.; The effect of chemical and surface properties of hydrogenated carbon overcoats on the tribological performance of rigid magnetic disks; IEEE Trans Mag; 1-93; 29 (1); 276

Figure 11: **A typical friction test output**



Time (hr)

CSS Testing

The results of drag tests have been correlated with the now-more-common CSS (Contact Start Stop) test in the literature[32]. The CSS test more closely matches the drive operating conditions by allowing the head to take off and land many times. CSS work was done to compare the heads prepared in the development system with the heads prepared in the manufacturing system. This served as a final validation of system to system matching.

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[32] Ganapathi, S.K. and Talke, F.E.; "Correlation between Contact Start Stop and Constant Speed Drag Testing in Magnetic Head-Disk Tribology"; ASME Journal of Tribology; 33; 1993

Atomic Force Microscopy

A TopoMetrix® AFM was used to examine the surface topology of the films. The manufacturer suggested optimum settings and numerous scans were made on several films. The samples were all on silicon wafer substrates. Better results were obtained with a "Supertip" than with a standard tip. The Supertip is much sharper and longer, and is thus less subject to the meniscus forces arising on samples saturated with atmospheric adsorbates. A tapping mode, which is sometimes[33] employed to reduce meniscus effects, was not used.

Breakdown Voltage of the Film

The breakdown voltage of the film was measured by applying a voltage across the film and measuring the current in the circuit. The voltage was gradually increased until a rapid increase in current was observed. The voltage present at the time of this rapid increase is considered the breakdown voltage of the film.

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[33] Strausser, Yale; Scanning Probe Microscopy; American Laboratory; April 1994; 20.

The Thesis Covers Five Areas

The transfer of the technology to a new site and new tool provided a good juncture to re-visit the film characterization and to gain additional understanding of the film properties. After conversations with the engineering groups on both sides of the process transfer, and with the thesis advisors at MIT, it was agreed that this thesis would examine:

1) The impact of sputtering parameters on disk drive performance.

   The disk drive performance metrics studied were friction and stiction. A 2^{5-1} fractional factorial experiment was run on the development system to investigate the impact of power, pressure, bias, and film thicknesses on drive parameters. Mechanically good production heads were coated in each leg of the factorial along with test wafers. The test wafers were measured using HFS, FTIR, and UV-Visible spectroscopy. The heads were used for friction, stiction, and breakdown voltage tests.

2) Matching the film using a different sputtering system.

   This includes a discussion of the differences between the two sputtering systems and the films they produce. Experiments varying the gas flow rate, gas composition and substrate bias in the manufacturing system were performed in order to match it to the development system. Wafers from these experiments were measured using HFS, FTIR, UV-Visible, and Raman spectroscopy. Operating conditions for the manufacturing system were chosen based on these results. Breakdown voltage testing and CSS testing were performed on heads coated in the manufacturing system in a direct comparison with heads coated in the development system.

3) The question of how thin the film can be and still be effective.

   It was acknowledged that this could not be completely resolved in the time available. An experiment was performed using goniometry and AFM to determine surface properties of the film as a function of thickness. The results are documented here.

4) Changes in manufacturing practices necessary to increase the throughput.

   The process is strongly influenced by preceding operations in the manufacturing flow. This section discusses some of the interaction between process steps and how interaction among the people involved was required to make the new operation successful.

5) Issues surrounding effective technology transfer

   This includes a description of the two sites' cultures and an analysis of the actions of a new company taking over both.

Organization
The first three of the topics in this thesis are experimental. The remaining two are based on observations of the business interactions of the company. The experimental work and the observation work are separated in this thesis for clarity. The results of the three experiments will be presented, followed by a discussion of the experiments. Topic four, changes in manufacturing practice; and topic five, technology transfer; are treated separately.

1) Deposition's impact on disk drive performance

A 2^{5-1} fractional factorial experiment was run on the development sputtering system. This was done to explore the sensitivity of the process to sputtering input parameters in advance of the delivery of the new manufacturing system. The inputs and the input ranges for the experiment were developed in conjunction with the development engineer after reviewing the literature and taking into account what could and could not be easily varied on a system that was used daily for manufacturing output.

The manufacturing engineer flew to the development site and remained there for 10 days in order to execute the experiment.

A 2^{5-1} with center point replicates design was chosen because:

1) It is a resolution V design, meaning that two factor interactions will be confounded only with three factor and higher order interactions[34].
2) Twenty experimental passes were all that could be executed in the allotted time, once the targeting runs prior and manufacturing verification runs after were added to the time budget.

The input variables and levels were:

Power
Pressure
Substrate Bias
Silicon overcoat thickness
Carbon middle layer thickness

All of except bias were run at 3 levels in the factorial: Low, High and Center. Bias was run at 2 levels. The deviations from the centerpoints varied between 30% and 75%. The magnitude of changes in the experiment parameters were well beyond the normal variance of day to day production.

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[34] Box, G.E.P., Hunter, W.G., and Hunter, J.S.; Statistics for Experimenters; Wiley Interscience; 1978; p 407.

The outputs analyzed, methods of analysis, and location of summary :

Deposition Rate	UV-Vis	Figure 14
Band Gap of the carbon film only	UV-Vis	Figure 15,16
Thickness of the trilayer stack	UV-Vis	Tables 3 & 4
Band Gap of the trilayer stack	UV-Vis	Tables 3 & 4
C-H bonding in the carbon film	FTIR	Figure 17
Hydrogen content of the carbon film	HFS	Figures 20-22
Stiction		
Increase over 24 hours of drag	Test stand	Tables 3 & 4
After 24 hours of drag	Test stand	Tables 3 & 4
Friction		
Shape of friction trace	Test stand	Tables 3 & 4
Increase over 24 hours of drag	Test stand	Tables 3 & 4
After 24 hours of drag	Test stand	Tables 3 & 4
Breakdown Voltage	Multimeter	Tables 3 & 4

Three complications appeared in this experiment; one was resolved:
The literature suggests substrate bias is an important contributor to film growth and structure[35,36,37]. That is why it was added to the experiment. The manufacturing use of the machine mandated that all the unbiased runs be made first and the biased runs be made second. This deviation from complete randomization was accounted for by making repeated centerpoint runs throughout the experiment -- the results of these repeated measures showed that the system was behaving consistently over time. Blocking the biased and unbiased runs did not introduce sequence-dependent effects into the experiment.

What remains an issue was that the power supply for the table bias was the same power supply used to bias the target. A splitting network was invoked to split the power supply output between the target and the table. There are no monitors on the machine to show how power is split. The result of this is that Bias is confounded with Power in this experiment. Looking at a plot of biased and unbiased deposition rates against power, the lines are parallel (Figure 12). This result suggests that either: 1) Bias had no effect on deposition rate and the difference was due to the transfer of power to the table, or 2) The deposition rate effect of bias was constant across the power settings. Since work on the new system with its independent power supplies showed deposition rate to be very sensitive to how the system was biased (Table 1), scenario (2) is more likely. This also matches statements in the literature[38], which indicate that these hydrogenated carbon films are sensitive to ion bombardment.

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[35] Vossen, J.L. and Kern, W.; Thin Film Processes; Academic Press Inc.; 1978

[36] Ohring, M.; The Material Science of Thin Films;Academic Press Inc.; p 130.

[37] Robertson, J.; "Mechanical Properties and Coordinations of Amorphous Carbons"; Physical Review Letters; Vol 68 (2); 1992

[38] Kasper,W., Bohm, H. and Hirschauer, B.; "The influence of electrode areas on radio frequency glow discharge"; Journal of Applied Physics; 71 (9) 4168; May 1992.

Figure 12: The effect of bias on deposition rate was independent of power

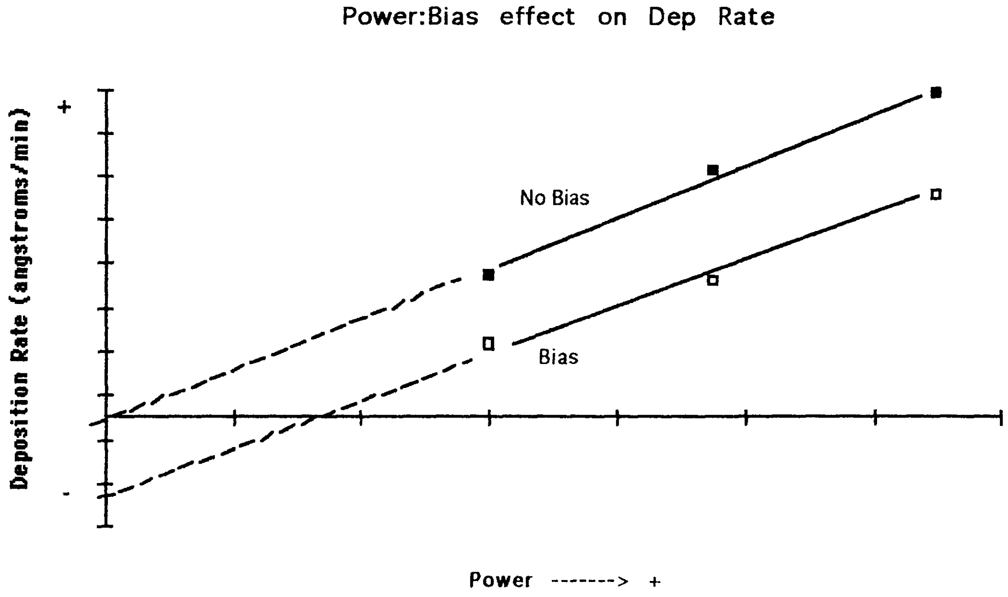

Table 1: Small changes in bias had a large impact on deposition rate in the MAN system

Condition	Relative Bias	Relative Eg	Relative Dep. Rate
Table floating	Meter disconnected	1.02	1.6
Matching network	14	1.04	2.0
Table grounded	- 1	1.00	1.0

The third complication is that Eg is known to be a function of film thickness[39]. A graph of this function is reproduced here (Figure 13) with permission from the author. It is not known if the same curve applies to other deposition conditions. Within some comparisons, the thickness varies quite widely from one sample to the next. In these instances, the results are shown two ways: 1) As they were measured, 2) With a correction for thickness. This correction is based on the standard deposition conditions. There is no guarantee that the Eg behavior of non-standard depositions -- those with bias, for example -- follow a similar trend. When this thickness correction is applied, a big assumption is being made. View the results with some jaundice where the thicknesses vary within a comparison.

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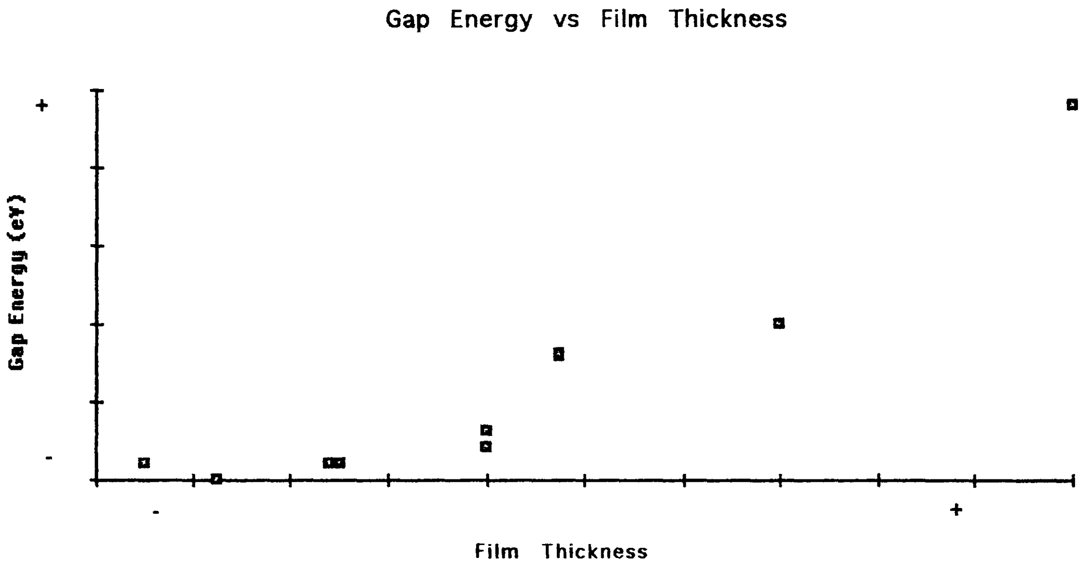
[39] Campos, F.; "Manufacturing Readiness Review"; Internal Document; July 1994.

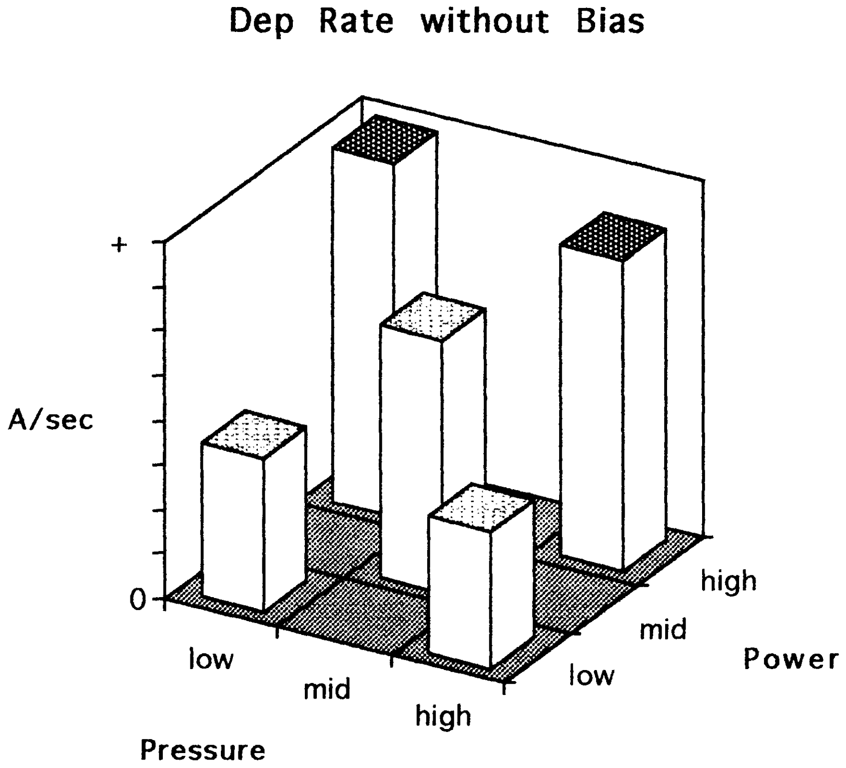
Figure 13: Optical gap is a function of film thickness



Deposition Rate

Of the input variables studied, the two with the greatest impact on deposition rate are power and bias. Pressure had little effect. The power and bias relationship has already been presented a in Figure 12 and in Table 1. The unbiased power/pressure relation is shown in Figure 14.

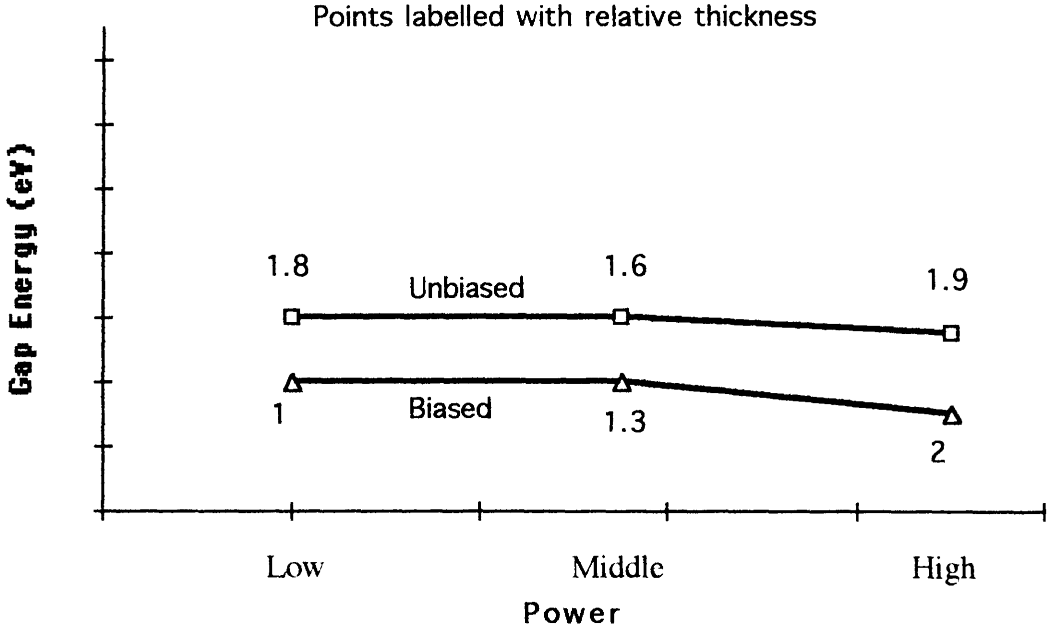
Figure 14: The impact of power and pressure on deposition rate



Band Gap Carbon Film Only
The band gap of the singular carbon film is shown both raw and corrected for thickness in Figures 15 and 16. If one believes that the thickness correction discussed earlier applies, it is clear that bias causes Eg to be more sensitive to power.

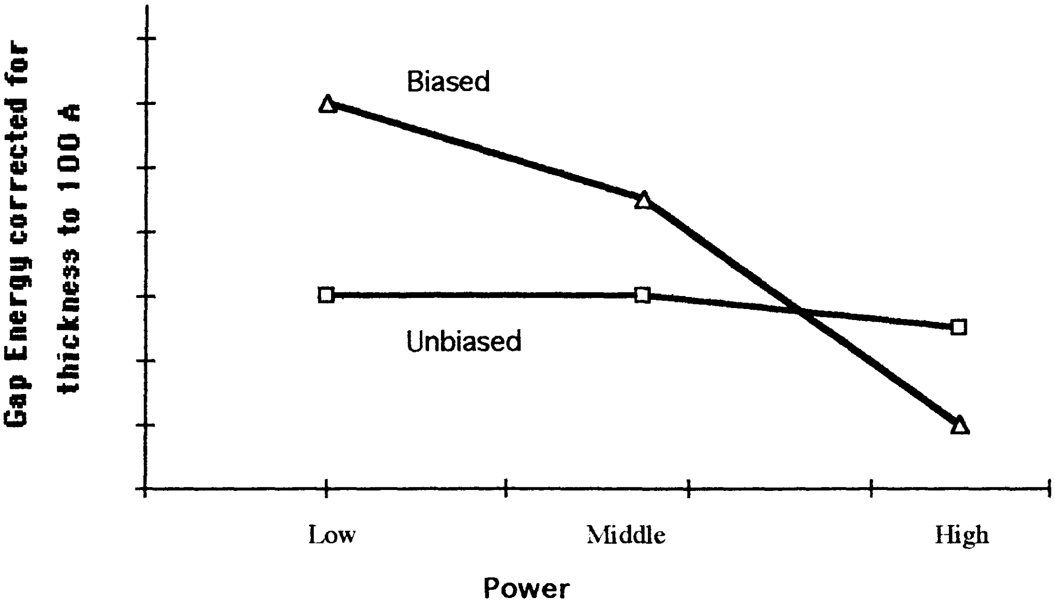
Next Page:

Figures 15 and 16 The effect of Power and Bias change depending on whether or not Eg is corrected for thickness



Power:Bias effect on Raw Eg

Points labelled with relative thickness



Power:Bias effect on Corrected Eg

FTIR Spectra

The FTIR peaks found in the amorphous hydrogenated carbon samples analyzed are detailed in Table 2. It is important to note that when comparing FTIR scans, the shape of the curve matters more than the amplitude. The amplitude of the trace can be affected by slight film thickness differences or by how well the sample couples to the crystal. The shape -- which peaks are present or absent and the ratios between the peaks -- is the indication of chemical bonding.

Table 2 FTIR peaks in study films

Wavenumber	Description	Reference
517	SiO_2 v1 mode	Chen[40]
565	Silicon crystal	Willardson[41]
609	Carbon in Silicon	Stallhofer[42]
610	Silicon crystal	Willardson
735	Silicon crystal	Willardson
820	Silicon crystal	Willardson
890	Silicon crystal	Willardson
963	Silicon crystal	Willardson
1105	SiO_2	Chen
1300	C-C stretch sp^3 Silicon crystal	Dischler[43] Willardson
1375	CH_3 symmetric deformation Silicon crystal	Nadler[44] Willardson
1448	CH_2 bending or CH_3 asymmetric bending Silicon crystal	Nadler Willardson
1579	C-C stretch aromatic sp^2	Dischler
1720	C=O	Colthup[45]
2865	symmetric CH_3 sp^3	Dischler
2925	asymmetric CH_2 stretch sp^3	Dischler
2960	asymmetric CH_3 stretch sp^3	Dischler
3300	triple bond CH sp^1	Dischler
3460	H_2O	Colthup

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[40] Chen, C.S. and Schroder, D.K.; "Vibrational Modes and Infrared Absorption of Interstitial Oxygen in Silicon"; Applied Physics A; Vol 42; 1987

[41] Willardson, R.K. and Beer, A.C.; Semiconductors and Semimetals, Volume 3: Optical Properties of III-V Compounds; Academic Press; 1967

[42] Stallhofer, P. and Huber, D.; "Oxygen and Carbon Measurements on Silicon Slices by the IR Method"; Solid State Technology; August 1983

[43] Dischler, B., Bubenzer, A. and Koidl, P.;"Bonding in hydrogenated hard carbon studied by optical spectroscopy"; Solid state communications; 48 (2); 1983

[44] Nadler, M. P., Donovan, T. M. and Green, A. K.; "Thermal annealing of study of carbon films formed by the plasma decomposition of hydrocarbons"; Thin solid films; 116; 1984

[45] Colthup, Daly, and Wiberley; Introduction to Infrared and Raman Spectroscopy, Third Edition; Academic Press; 1990

FTIR vs. Deposition Conditions

As depicted in Figure 17 and 18, deposition conditions had little effect on the FTIR peaks in the C-H stretching region. The only signal significantly different from the others is the "DEV standard". All these films were run on the DEV, but the DEV standard was run at different time than the others. It was run approximately 3 months later. This suggests that variance over time in the system is at least as important as other changes in deposition conditions.

Figure 17: Deposition conditions had little effect on the C-H stretching region

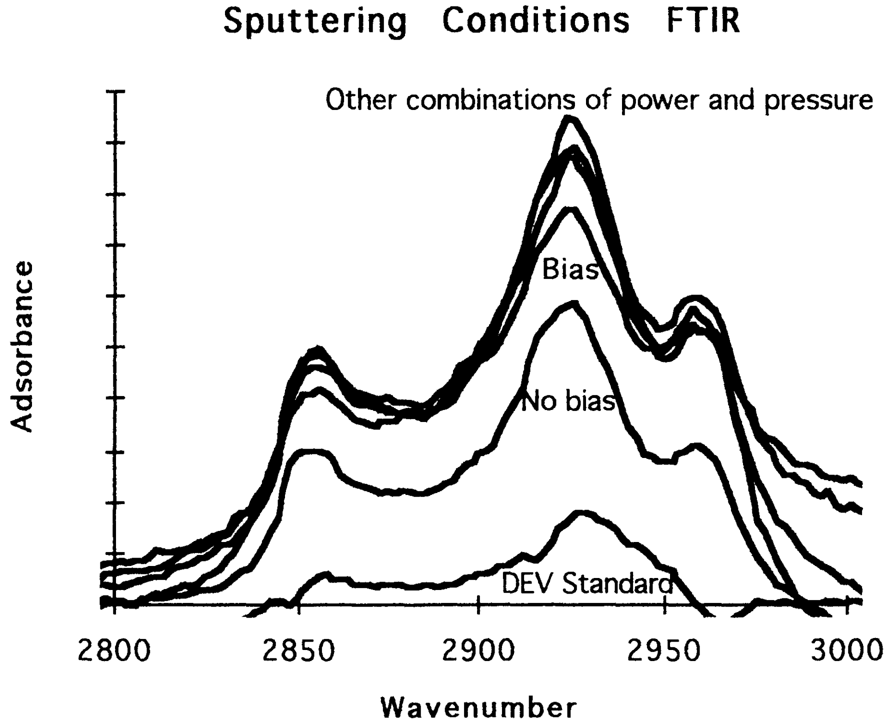
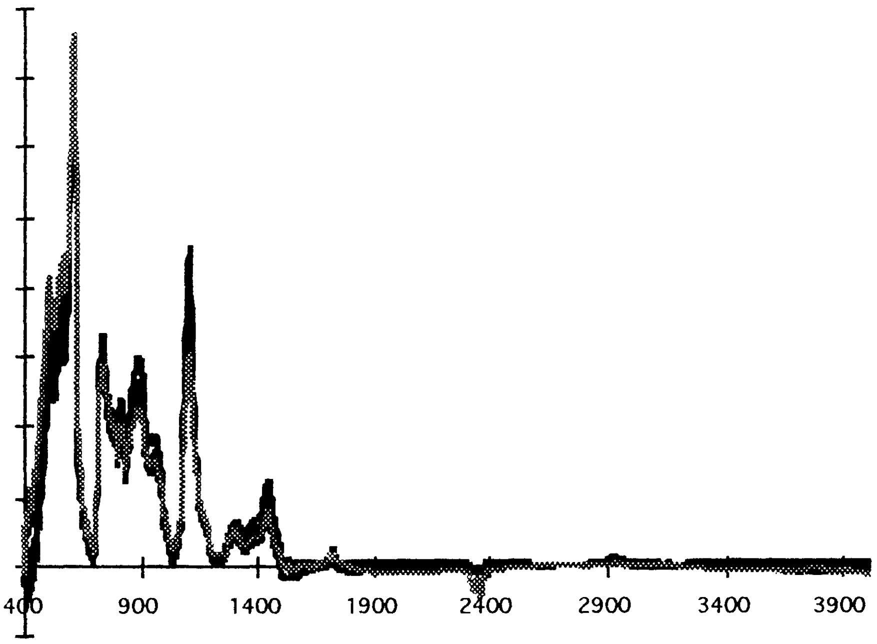


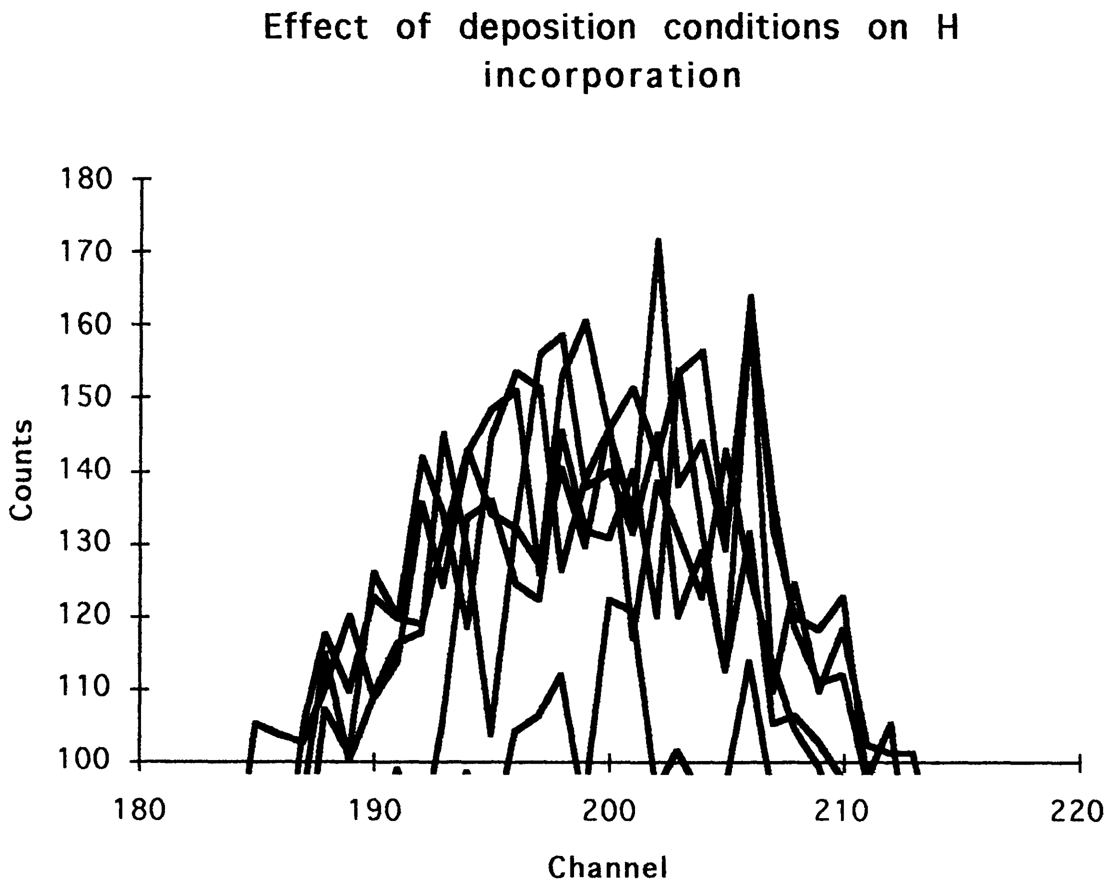
Figure 18: Full FTIR scan of sputtering conditions experiment



Both the 2800 to 3000 graph of the CH bonding region and the 400 to 5000 graph that is dominated by the silicon substrate peaks lead to the same conclusion: The FTIR spectra of these films is largely insensitive to sputtering power, pressure, and bias.

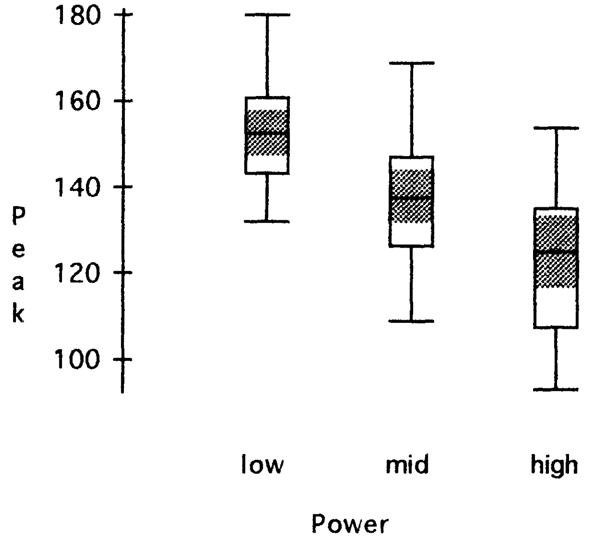
HFS vs. Deposition Conditions

Figure 19: Effect of power, pressure and bias on H incorporation



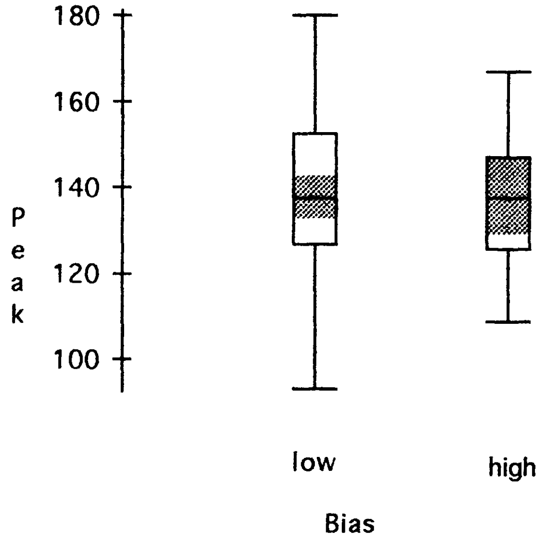
Because of the noise seen in the graph above, the data was analyzed statistically. The results from the 2^{5-1} experiment on the development system are shown below as box plots. The format of the box plots is as follows: The top and bottom of the box represent the 75 and 25 percentile of the ranked data in that group. The bar in the box is the median (50 percentile). The wings on the box cover the last data point not further than 1.5 times the box height from the top or bottom of the box. Points beyond are shown as circles. This corresponds to Tukey's box plot standard. The shaded region in the box is the 95% confidence interval for the median.

Figure 20: **Sputtering power (a linear input to deposition rate) controls H in the DEV system**



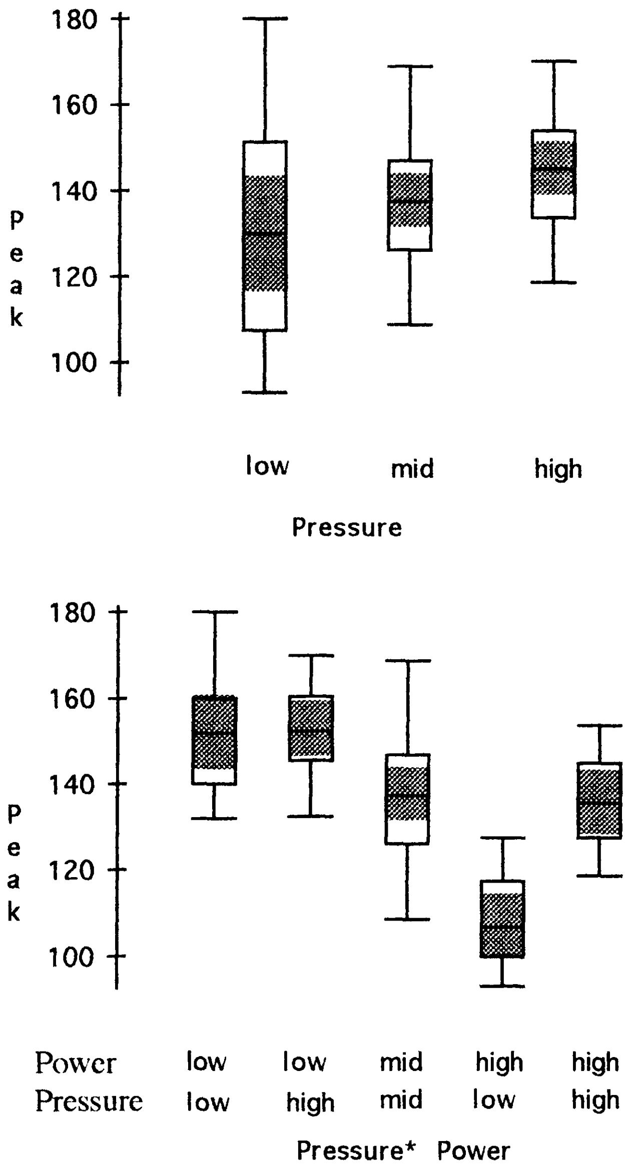
The amount of hydrogen included in the film is inverse to the power supplied to the deposition.

Figure 21: **Sputtering Bias has little effect on total hydrogen**



No distinction is evident in total hydrogen inclusion between biased and unbiased runs.

Figure 22: Sputtering Pressure Effects



Pressure alone has little effect, although the ANOVA states that the result pictured is significant. But Pressure * Power clearly has an impact on the amount of hydrogen incorporated into the film.

Regression

The impact of the experiment's input parameters on output parameters is presented in Table 3. The outputs were fitted using RS1's multiple linear regression package, and verified using DataDesk® 4.2. The resulting models were checked for residual normality and for outliers. The significant input parameters are summarized for easy comparison in Table 4. An arc connecting two inputs signifies that their interaction term was significant.

As an example of how to interpret Table 3, consider the stack thickness. The regression of measured thickness against the 2^{5-1} factorial inputs indicates that the following factors are significant. Significant here is defined as having less than a 10% chance of being a random occurrence.

Carbon Bias
Carbon thickness
Silicon thickness
Silicon thickness * Carbon thickness
Pressure * Carbon thickness

Carbon deposition pressure (Carbon Pressure in the table heading) is not significant by itself, but interacts with carbon thickness in a significant way.

Similar information is presented in a different way in Table 4. Here each significant effect has its t-value listed. This allows comparison of how significant each effect is. It is clear from Table 4 that carbon thickness and silicon thickness are the most significant inputs to the stack thickness. The residual degrees of freedom are given to allow interested readers to look up the α in a student t table.

Adjusted R^2 indicates that a linear combination of the five significant factors accounts for 88% of the variation seen in stack thickness measurement. Significance in the regression does not mean that these are causal factors for the observed effect. "Correlation does not imply causation."[46] The significant inputs are a good base to support additional exploration of process linkages.

Regression of Thickness and Optical Gap of the Stack

The UV-Visible spectrophotometer is used to monitor production by measuring the entire slider coating stack, not just the carbon film. Since there is not a program dedicated to the stack, the carbon film program is employed. Eg is somewhat muted by the silicon layers. Thickness is fairly well represented. Silicon thickness comes through one for one, while additional carbon thickness comes through at 80%. That is, 10 angstroms of additional a-H:C will show up as 8 angstroms of stack thickness in this admittedly artificial measurement. The high adjusted R2 for the stack thickness and optical gap measurements show that the UV-Visible spectrophotometer, despite its problems, is an effective monitor for the film stack deposition. It is sensitive to film parametric changes induced by changing deposition conditions.

Regression of Stiction

The data used in both the stiction and friction regressions is all from the 2^{5-1} experiment. Two heads from each split of the factorial were subjected to a 24 hour low speed drag test. The average ending stiction and increase in stiction over the course of the test were extracted from plots of stiction vs. time.

The underlying carbon film has a clear impact on stiction. In both the 24-hour stiction and the increase in stiction, the same two carbon film input parameters are significant. Carbon bias interacts with carbon thicknesses in both models. A silicon thickness interaction also appears in the 24-hour model. The fact that 25% of the variance in stiction can be accounted for by changes in a subsurface film is unexpected.

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[46] Every statistics professor in the world says this

Regression of Friction

The link between friction and input parameters was less visible than in the stiction data. Adjusted R2 was only 14 to 21%. Carbon deposition pressure and silicon overcoat thickness were common to both the increase in friction and the 24-hour friction models. Again, there appears to be an interaction between the surface film and the subsurface layers in determining friction behavior. No correlation between the time-to-peak friction and any deposition parameter was observed.

Regression of Breakdown Voltage

The breakdown voltage of the film stack is sensitive to both carbon and silicon layer thickness. This is as expected, but the coefficient on the silicon thickness is negative. Increasing the silicon overcoat thickness gives a lower breakdown voltage in this data. Beyond the film thicknesses, carbon deposition pressure plays a large role in determining breakdown voltages. Deposition pressure has a strong effect, as can be seen in Figures 23 and 24. It drives both the low and high tails of the breakdown voltage distribution.

Figures 23 and 24: Pressure is an important input to breakdown voltage

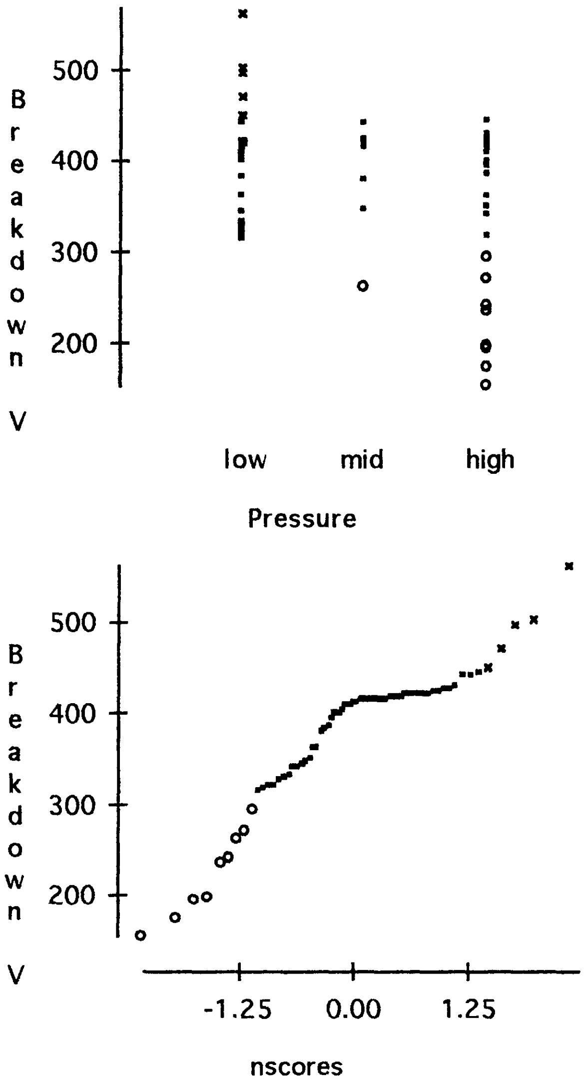

Table 3: Regression Summary

				Inputs		
Output	Adjusted R^2	Carbon Bias	Carbon Power	Carbon Pressure	Carbon thickness	Silicon Thickness
Stack Thickness	0.88	Significant		Not	Significant	Significant
Stack Eg	0.87	Significant	Not	Not	Not	Significant
Increase in Stiction	0.27	Significant	Significant		Not	
Stiction at 24 hours	0.24	Significant	Significant		Not	Not
Shape Friction Trace	0					
Increase in Friction	0.14			Significant		Significant
Friction at 24 hours	0.21		Not	Significant		Significant
Breakdown Voltage	0.16			Significant	Significant	Significant

Table 4
Regression t-values (absolute) from factorial experiment on DEV system
Only significant values are shown

	Stack Thickness	Stack Eg	Increase in Stiction	End 24 hrs. drag Stiction	Increase Friction	End 24 hrs. drag Friction	Breakdown Voltage
Bias	2.2	4.9	1.7	2.9			
Power			2.6	1.8			
Pressure					2.2	2.0	2.8
Carbon thickness	10.2						1.7
Silicon Thickness	4.5	7.2			1.8	2.6	2.1
Bias*Pressure							
Bias*C Thickness			2.1	2.6			
Bias*S Thickness		3.9		2.1			
C Thickness*S Thickness	3.1	2.5					
Power*C Thickness			1.9				
Power*S Thickness						2.0	
Power*Bias		3.9					
Pressure*C Thickness	2.4	4.5					
Adjusted R^2	0.88	0.87	0.27	0.24	0.14	0.21	0.15
residual degrees of freedom	13	10	25	24	33	31	61

2) Adapting to a different sputtering system.

The literature clearly states that the structure and performance of DLC films is sensitive to deposition conditions[47,48,49,50,51,52,53,54,55,56]. It is less clear on which deposition conditions are most important to control. This was the jeopardy in choosing a different sputtering system for the manufacturing site. Nobody knew precisely what changes to expect. Further, the film development had been done before the corporation had acquired advanced tools to characterize the film. The operating point was chosen with limited knowledge of the response surface surrounding it. These two facts: the known sensitivity of the film to deposition conditions, and the largely unknown response surface on drive performance, framed this thesis work.

Comparison of the two sputtering systems
Both sputtering systems use rf glow discharge plasmas to remove material from the target and deposit it on the substrate. Both sputtering systems use a rotating table to carry the substrates under the target. Table rotation is constant throughout the deposition. The substrates thus pass multiple times under the target during film growth.

The two systems were set up to be as identical as possible. Input parameters -- gas flow rate, gas composition, pressure, power, table spacing, table temperature, target shape, size, mounting and composition (same vendor) -- were matched wherever possible. This done, the differences between the systems were largely those of geometry.

The geometry of the development DEV 540 was comparatively open (Figure 25). Gas enters next to the target and exits around the table to the throttled pump stack.

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[47] Bhushan, B., Kellock, A. J., Cho, N. and Ager, J. W.;"Characterization of chemical bonding and physical characteristics of diamond-like amorphous carbon and diamond films"; Journal of Materials Research; Vol 7 (2); 1992

[48] Cho, N. H., Viers, D. K., Ager, J. W., Rubin, M. D., Hopper, C. B., Bogey, D. B.; "Effects of substrate temperature on chemical structure of amorphous carbon films"; J. Appl Physics. 71 (5); 3-1-92; 2243.

[49] Dischler, B., Bubenzer, A., and Koidl, P.; "Hard Carbon Coatings with low Optical Adsorption"; Applied Physics Letters; Vol 42 (8); April 1983

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[51] Marchon, B., Heiman, N. and Khan, M. R.; "Raman and Resistivity investigation of carbon overcoats of thin-film media: Correlations with tribological properties"; Journal of Applied Physics; Vol 69 (8); 1991

[52] Tsai, H. and Bogy, D.B.; "Critical Review -- Characterization of diamondlike carbon films and their application as overcoats on thin film media for magnetic recording"; J of Vac Sci A; 5 (6); 11-87

[53] Tsai, H., Bogy, D.B., Kundmann, M.K., Veirs, D.K., Hilton, M.R., and Mayer, S.T.; Structure and properties of sputtered carbon overcoats on rigid magnetic media disks; J. of Vac. Sci. Technology A; 6 (4); 7-88

[54] Agarwal, S. and Li, E.; Structure and Tibological Performance of Carbon Overlayer Films; IEEE Transactions on Magnetics Vol 29:1; Jan 1993

[55] Yoshikawa, M., Katagiri, G., Ishida, H., Ishitani, A.; Raman spectra of diamondlike amorphous carbon films; J Appl. Phys.; 64 (11); 12-88

[56] Robertson, J.; "Mechanical Properties and Coordinations of Amorphous Carbons"; Physical Review Letters; Vol 68 (2); 1992

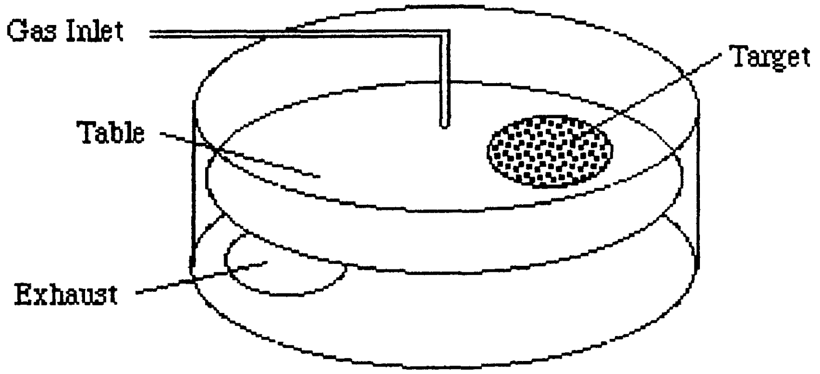


Figure 25: The DEV 540 development system had an open configuration

The geometry of the manufacturing MAN system was comparatively closed (Figure 26). Gas enters a pie shaped canister surrounding the target and deposition area. The exits from this area are 1/4 inch to 3/16 inch gaps and holes. These gaps and holes are on the order of the mean free path of the gas at sputtering pressure.

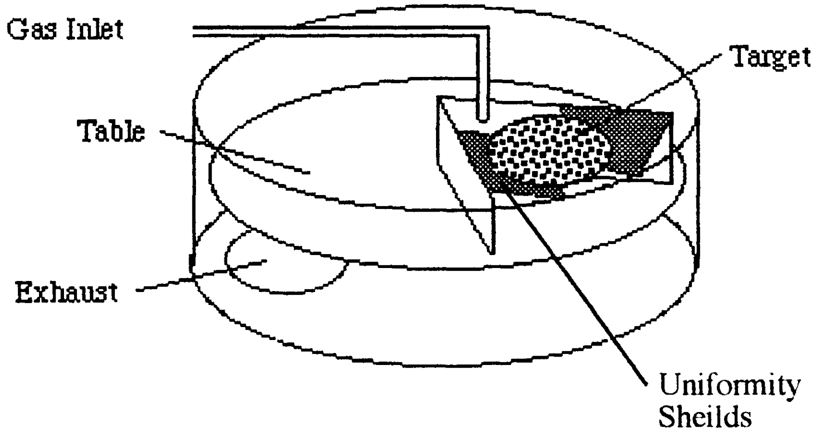


Figure 26: The new MAN system chosen for manufacturing had a comparatively closed configuration

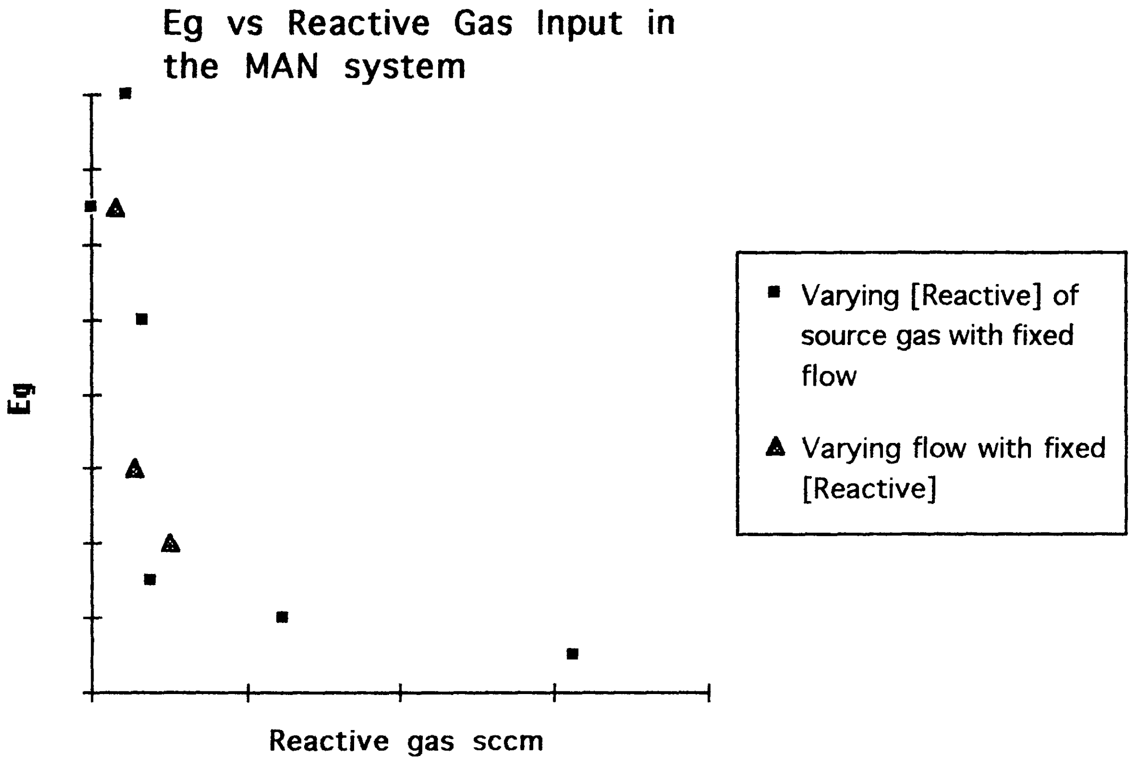
The manufacturing system thus has components of Knudsen flow in the vicinity of the target that the development system does not.

Other results of this difference in shielding lie in deposition rate and uniformity. The DEV does not have shaping shields installed. This gives it a higher deposition rate than the MAN, at the cost of a narrower uniform zone.

Sputter System Matching

The film produced in the development system had an Eg of 2. This Eg measurement is repeatable to within 0.015. This was our target for the manufacturing system. Running the new system with all the inputs matched that could be matched, the Eg came in at 1.9 or 1.91. Varying power and pressure 50% in either direction had little to no effect on the band gap. Bias had an effect, but was not a variable we wanted to change between the systems. Experiments found that varying the gas flow rate had an effect. Varying the reactive gas concentration in the input gas stream had an effect. The results of the two gas experiments can be combined by using reactive gas introduced as the abscissa[57]. This gives the plot shown in Figure 27. It is clear that total reactive gas supplied is a critical parameter. In order to match the Eg of the development system, the manufacturing system has to introduce less reactive gas into the chamber.

Figure 27 Reactive Gas Input is a Critical Parameter



Three theories were suggested by people within the engineering group to explain why less reactive gas is required in the manufacturing system to match the optical gap of the development system:

Gas depletion
Chamber dwell time
Pressure the in deposition region

---

[57] Credit for this idea goes to Jim Getz.

Gas depletion

The gas depletion theory suggests that the Eg curve becomes steep at low reactive gas rates because the reactive gas is being used up in the reaction with the film. To test this theory, the molar flowrate of reactive gas introduction was compared to the molar uptake rate of the reactive species by the film. The ideal gas law was assumed to calculate the moles of reactive gas and by stoichiometry, the moles of hydrogen supplied to the chamber. This is a good approximation because the sputtering pressure is well within the ideal gas range. To calculate the moles of hydrogen in the film requires knowledge of the film hydrogen content and density. These numbers, 40% and 1.7 grams/cc respectively, are found in an investigation of a similar film by Bhushan.[58] Carrying through the calculation shows that the reactive gas supplies more than 100 times the hydrogen incorporated into the film. The steep slope of the Eg curve is not caused by any significant depletion of the sputtering source gas. It follows that differences between the systems are not due to this effect.

Chamber Dwell Time

The chamber dwell time theory ties to the fact that the uniformity shields in the MAN system cause the deposition rate to be 1/2 the rate of the DEV system. The substrates spend more time in the MAN system and experience more rotations through the deposition zone. The chamber dwell time theory suggests that this added time in the chamber allows more hydrogen to be included in films produced in the MAN system.

For the chamber dwell theory to hold, hydrogen flux to the substrate surface would have to be a limiting factor. The time for a monolayer of reactive gas to form, based on a Boltzman distribution of molecular energies is:

$$t_{ml} = \frac{1}{\Gamma \frac{\pi}{4} \frac{d_0^2}{pc}} = \frac{4}{nv \frac{\pi}{4} \frac{d_0^2}{pc}}$$

Where

v is the average reactive gas molecule velocity
gamma is the reactive gas molecule flux to the surface
n is the number density of reactive gas molecules
d_0 is the diameter of the reactive molecule
pc is the surface packing factor

The equation above assumes a unity sticking coefficient -- all the molecules which arrive at the surface stick.

Carrying out this calculation shows that the time to form a monolayer, even with a sticking coefficient of one in one thousand, is much less than the rotation time. This reduces the chamber time theory to the number of passes the substrate makes under the deposition zone. The deposition time is twice as long and the table revolves twice as fast in the MAN system. The MAN system thus generates four times the number of revolutions during a deposition cycle. There could thus be four times as many reactive gas monolayers sandwiched into the film. This might account for the less reactive gas required in the MAN system.

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[58] Bhushan, B., Kellock, A. J., Cho, N. and Ager, J. W.;"Characterization of chemical bonding and physical characteristics of diamond-like amorphous carbon and diamond films"; Journal of Materials Research; Vol 7 (2); 1992

It does not, however, match the data. A small change in reactive gas leads to a large change in observed Eg. That small change in reactive gas has little effect on the monolayer formed during the rotation. The monolayer will still form very rapidly compared to the rotation time. The substrate surface as it enters the deposition zone for the next pass will look the same. The chamber dwell time theory cannot explain the Eg offset between the systems.

Pressure in the deposition region

The pressure in both systems is controlled by a variable angle vane valve in front of the pump throat. The capacitance manometer which measures pressure during deposition is located in a similar position in front of (on the chamber side of) this vane valve. The pressure at the vane valve is assumed to be equal to that measured by the capacitance manometer because the two are in close proximity.

The pressure in both the manufacturing and develop systems is controlled to the same value. The path from the deposition zone to the vane valve is roughly the same in each system. The gas flowrate is the same into both systems. That leaves the pie shielding as the most significant difference in configuration between the systems.

A conductance model was developed to test the theory that the real pressure in the deposition zone drove the differences between the systems. In gas dynamics, pressure drop is related to flowrate by the conductance:

$$\text{Pressure Drop} = \frac{\text{Gas Flowrate}}{\text{Conductance}}$$

Calculating conductance requires knowledge of the pressure and geometry in the system. The ratio of the mean free path of the gas to the characteristic dimension of the flow channel determines the flow regime. Different flow regimes require different calculations. This reflects the shift in the governing mechanisms in the different regimes. If the mean free path is large relative to the container dimensions, gas molecules collide most frequently with chamber walls. If the mean free path is small compared to the chamber dimensions, gas molecules collide most frequently with themselves.

The gas flows in these sputtering systems span a flow regime that is difficult to characterize. It is called the transition zone because it is intermediate between two well-characterized flow regimes. The smallest geometries in the sputtering systems drive flow dynamics at the lower end of the transition zone near the regime called "molecular flow". Gas molecules collide most often with walls in molecular flow. The largest geometries in the sputtering systems drive flow dynamics at the upper end of the transition zone close to the regime known as "continuum flow". Gas molecules collide most often with each other in continuum flow. Molecular flow and continuum flow approximations are used to create a simple model to compare the two sputtering systems.

Two conductances were calculated to model these sputtering systems. One was the conductance from the target area to the pump. Because this region is similar in both sputtering systems, the same equation was used for both. The characteristic dimension is large compared to the mean free path. The path from the target area to the pump was modeled as several straight pipes in parallel. The continuum flow equation for long straight pipes, called the Hagen-Poiseuille equation, was used to approximate conductance in this region:

$$C = \frac{\pi d^4}{128 \eta l}$$

d	diameter of pipe
η	dynamic viscosity of gas
l	length of pipe

The second conductance -- through the holes and gaps in the manufacturing system's pie shielding -- is unique to the manufacturing system. The conductance model uses molecular flow equations to represent the conditions in this smaller geometry region. Molecular flow conductance factors, called the transmission probabilities, have been tabulated for a large number of shapes. The values used to compare these systems came from O'Hanlon[59]. The conductance calculation is:

$$C = \frac{av}{4} A$$

a	transmission probability
v	average thermal velocity of gas
A	cross sectional area of flow path

Conductances in series add like resistances in parallel. The real pressures in the target region of each system can thus be estimated as:

Manufacturing System

$$P_{\text{real}} = \frac{Q}{\left(\frac{1}{C_{\text{target-pump}}} + \frac{1}{C_{\text{pie shield}}} \right)^{-1}} + P_{\text{pump}}$$

Development System

$$P_{\text{real}} = \frac{Q}{\left(\frac{1}{C_{\text{target-pump}}} \right)^{-1}} + P_{\text{pump}}$$

Q is the input flowrate. When Q in the manufacturing system is lowered until the real pressures predicted by these equations match, the optical gaps match too. When the flowrates are the same in each system, the pressure in the deposition zone of the MAN is nearly double that in the deposition zone of the DEV.

This conductance model explains the optical gap difference between the systems. The difference between the systems is due to pressure differences induced by the pie shielding in the manufacturing machine.

A paragraph in Sawin and Reif[60] explains why the deposition pressure fits the data and the chamber dwell time does not. It states that the chemical reactions in reactive sputtering occur primarily in the plasma when the substrates are held at room temperature. This explains why the pressure of the reactive species in the deposition zone, and not the molecules adsorbed on the surface between deposition passes, determines the optical gap. There is insufficient energy outside the plasma to activate the bonding reaction at the wafer surface.

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[59] O'Hanlon, John; A User's Guide to Vacuum Technology, Second Edition;Wiley Interscience, 1989

[60] Sawin, H. and Reif, R., Class notes 10.616J; MIT; 1995

The engineering group chose to run the manufacturing system with matching flowrate rather than with matching deposition zone pressures and optical bandgap because:

1) It was more stable. Two important output characteristics, thickness uniformity and breakdown voltage, were more consistent under the higher flow condition. This may be because the system was not operating in the high slope region of Figure 27, but in the lower slope region.

2) The difference the flowrate choice imparted to the film was not measurable by FTIR or in-use measurements. Raman results and HFS results favored the higher flow for process matching. These will be discussed below.

Reactive Gas Input FTIR results :

Figure 28 shows the changes found in the C-H stretch regime due to changes in the reactive content of the sputtering source gas. Only small differences are seen between 0% and 10% reactive component in the input gas. It is only when the reactive component is raised to 25% that there is a significant increase in C-H bonding in the film. In the lower concentrations, there is no FTIR evidence of anything except sp^3 bonding. In the 25% film, there is more sp^3, but there is also evidence of sp^2 (1579 cm-1) and sp^1 (3300). This matches the statement by several researchers[61,62] that as the hydrogen content rises the film will become more graphitic or polymeric and thus softer. Dischler feels there is a direct correlation between the area under the FTIR curve and the amount of bonding in the film. This requires that the earlier warning about amplitude of FTIR peaks is ignored. Assuming Dischler's relationship holds here, Figure 29 is a graph of the integral of the C-H peaks plotted against reactive gas content.

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[61] Robertson, J.; "Mechanical Properties and Coordinations of Amorphous Carbons"; Physical Review Letters; Vol 68 (2); 1992

[62] Yoshikawa, M., Katagiri, G., Ishida, H., Ishitani, A.; Raman spectra of diamondlike amorphous carbon films; J Appl. Phys.; 64 (11); 12-88

Figure 28: **FTIR vs. Reactive Fraction**

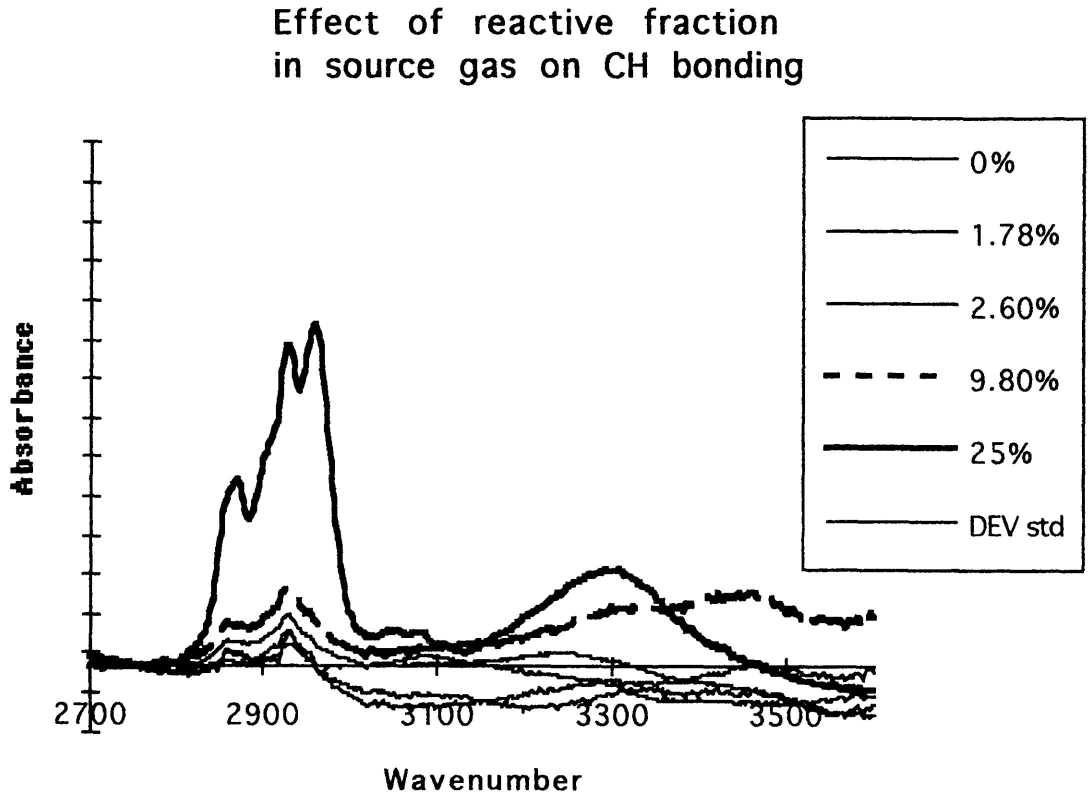
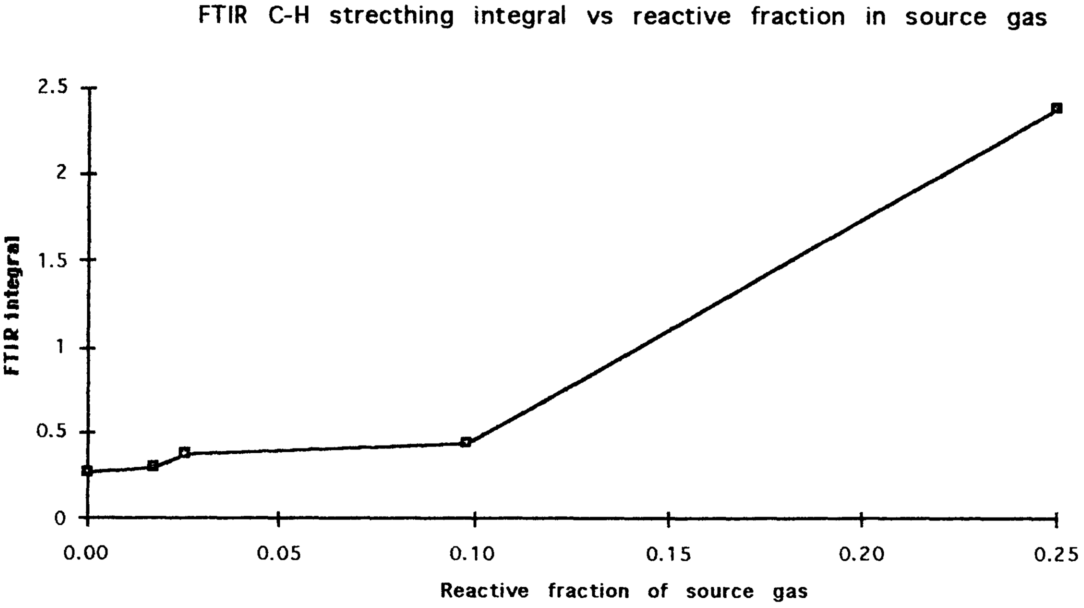


Figure 29: **Integral of CH bonding region vs. reactive fraction**



Flow FTIR results :
Figure 30 shows that there is no difference between the low flow and high flow FTIR traces from samples prepared in the MAN system. Figure 31 is a similar comparison, but with a DEV film holding the high flow position. The MAN, if one believes that one can integrate under the curve to quantify results, has somewhat more sp^3 character.

Figure 30: **There is little difference recorded by the FTIR between low and high flow.**

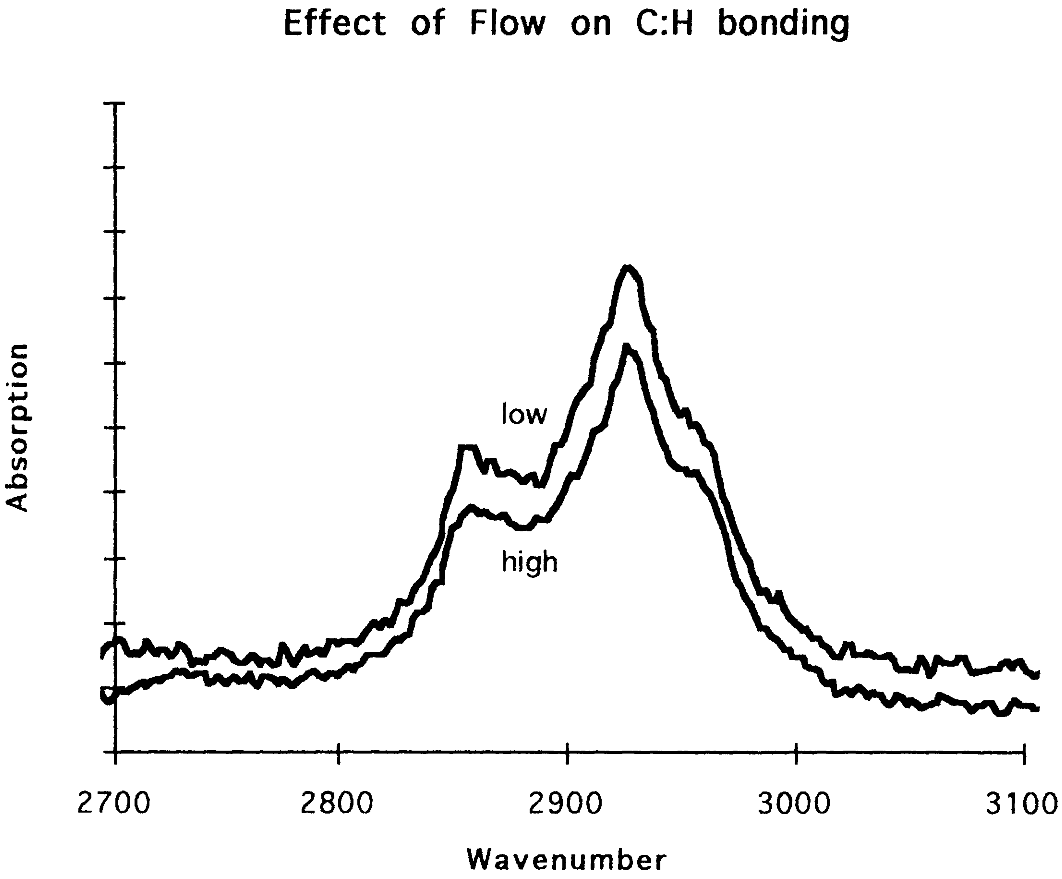
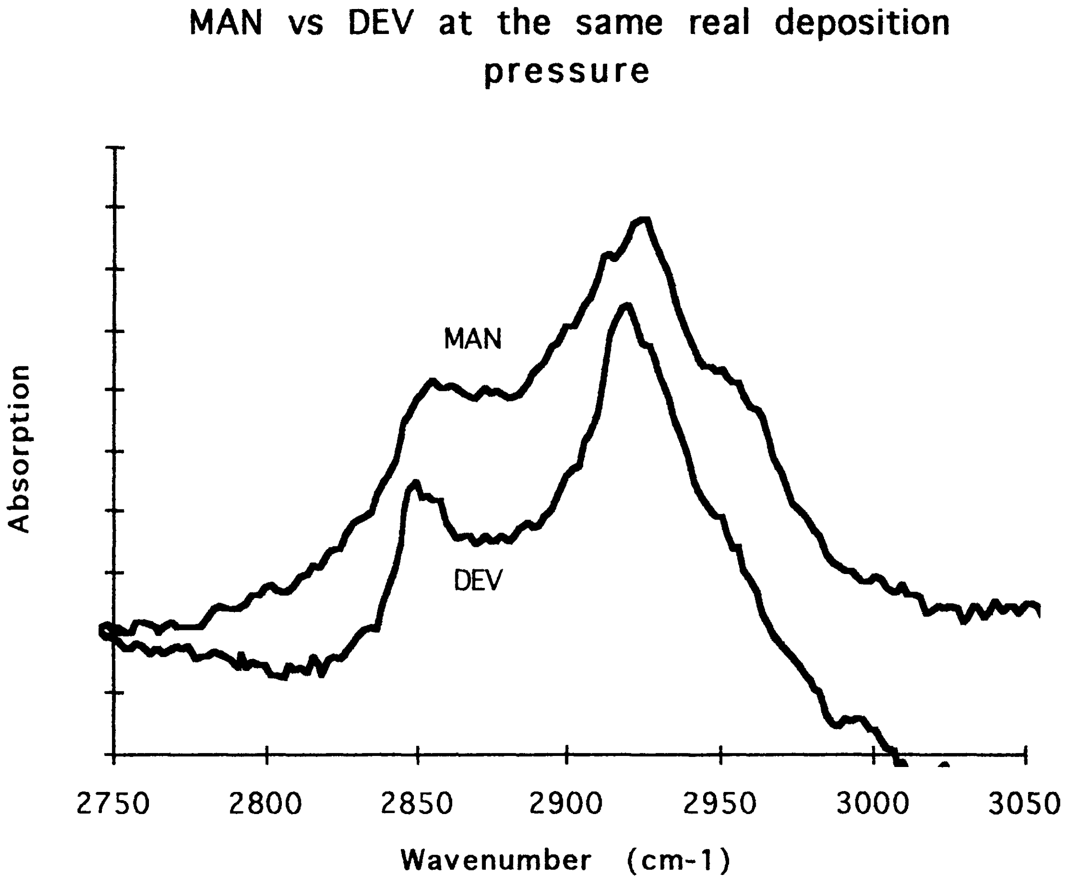


Figure 31: **The difference between the sputtering systems is small when the deposition pressure is matched.**



HFS results (Figures 32 through 34):

The HFS results show that, to the first approximation, all the films contain similar amounts of hydrogen. This matches the result obtained by Bhushan et al[63]. The only film to show an immediately obvious difference was the 0% run. Statistical analysis of the HFS data shows differences between films produced in the MAN using different gas flowrates. and between the DEV and the MAN. The best match between the DEV and MAN systems is obtained using the high flow in the MAN system.

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[63] Bhushan, B., Kellock, A. J., Cho, N. and Ager, J. W.;"Characterization of chemical bonding and physical characteristics of diamond-like amorphous carbon and diamond films"; Journal of Materials Research; Vol 7 (2); 1992

Figure 32: Except for the 0% run, the raw data is difficult to interpret

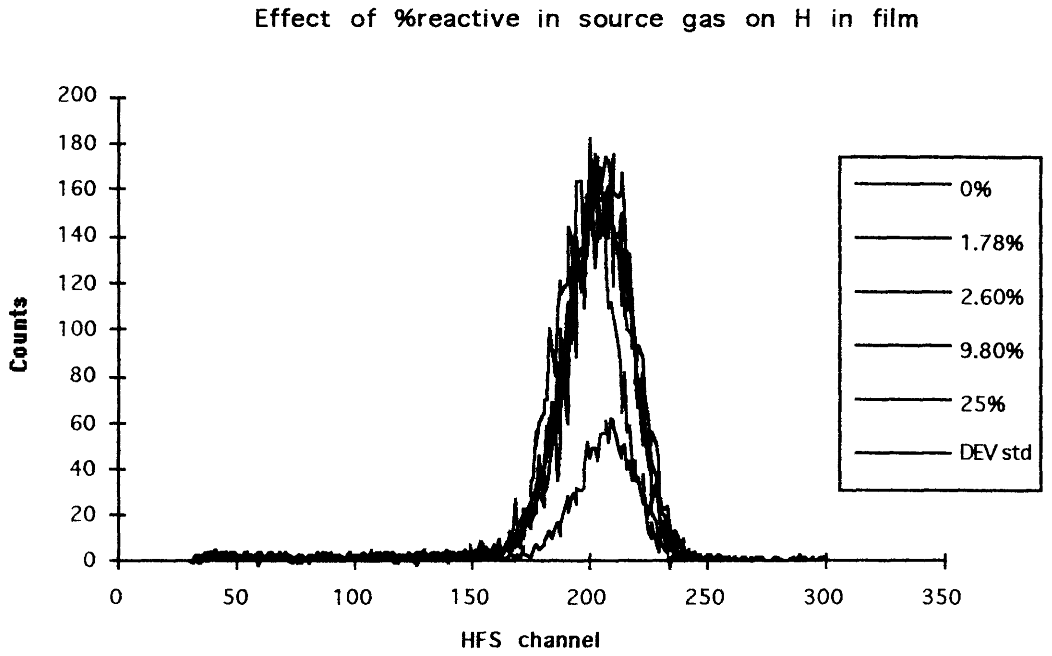
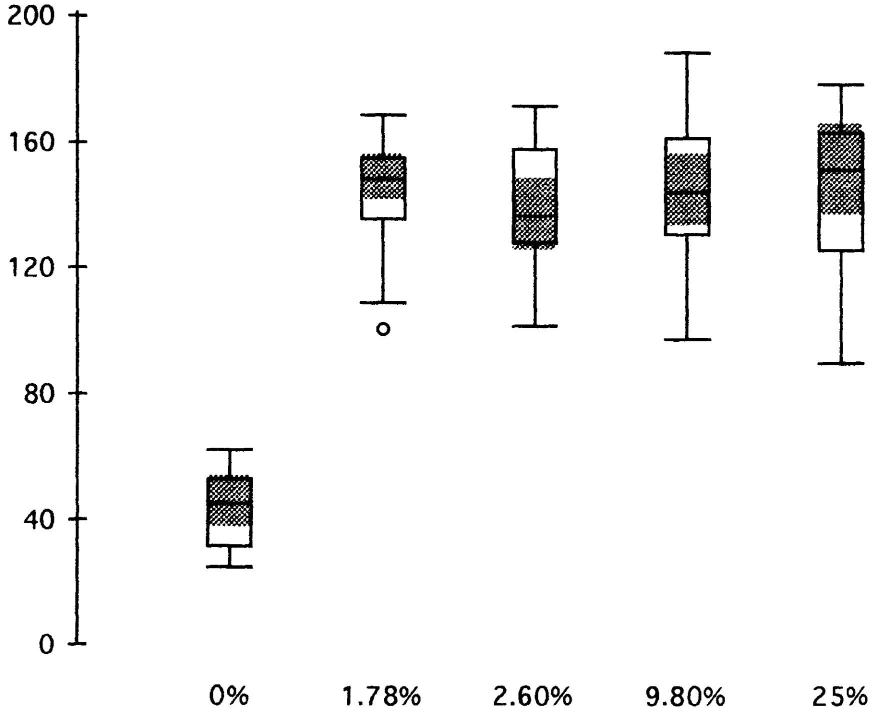
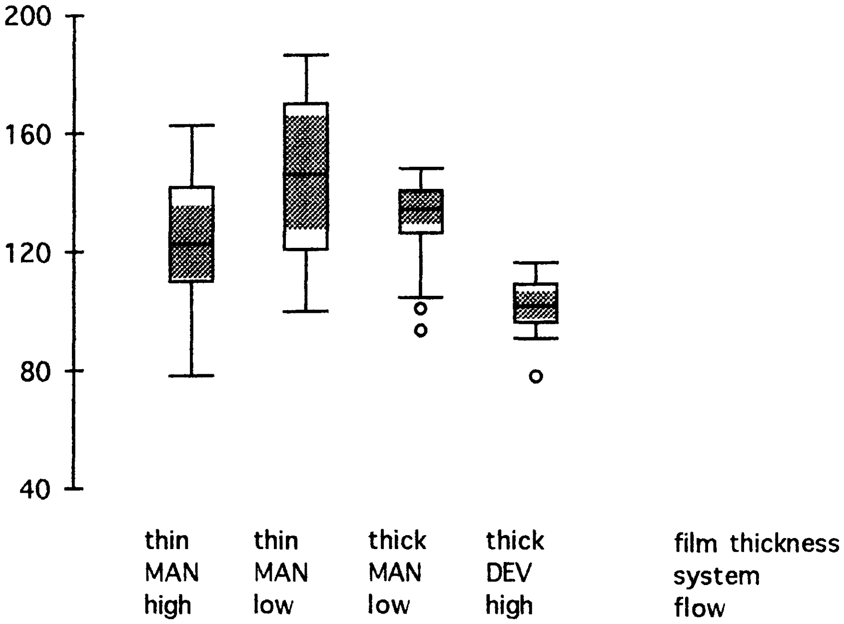


Figure 33: % Reactive in the source gas had no impact on measured Hydrogen uptake



The result shown in Figure 33 is incongruent with the FTIR integral results. It adds credence to the suspicion that the FTIR is more sensitive to sp^3 bonds than it is to sp^2 bonds. Alternatively, it bolsters the argument that to integrate under the FTIR curves is not advisable.

Figure 34: **Matching the flowrates between the systems better matched H incorporated**



Note in Figure 34 that there are two MAN low flow samples. The first of these was a thin sample, the second a thick. The DEV sample was similarly thick. The different thicknesses were normalized to be presented on the same scale. This is allowed because to the accelerator, all the films used in this study are thin. There is no appreciable difference between a hydrogen atom ejected from the bottom of the film or the top.

It is good that there is no statistical difference between the two samples which are based on the same deposition conditions. The thicker samples show less scatter because the thicker films have a better signal to noise ratio.

Raman results

The Raman data was analyzed by first subtracting out a linear baseline and fitting the peaks at 1360 and 1550 to obtain an Id/Ig ratio. Figure 35 shows the raw data minus baseline overlaid with the fitted curves. Table 5 lists the peak positions and Id/Ig ratios. The high flow films produced in the development system and manufacturing system are quite similar. A low flow into the MAN system gives quite different results. In this sample more so than in the others, the D peak is almost obscured by a high level of background fluorescence.

Figure 35: **Raman data shows effect of gas flow in matching site to site**

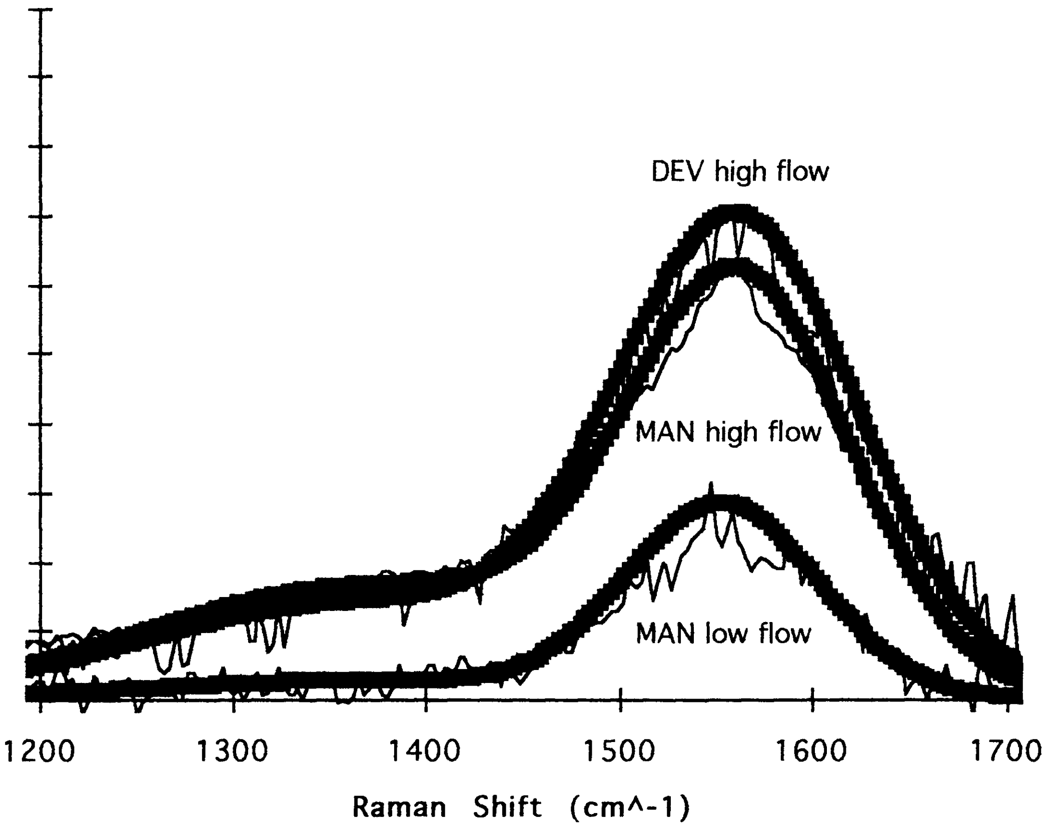


Table 5: Raman Comparison

System/Conditions	DEV high flow	MAN high flow	MAN low flow
G peak location	1562	1562	1553
D peak location	1360	1370	1360
Id/Ig	0.35	0.55	0.2

The conductance calculations explain why lowering the flowrate in the MAN raises the optical gap to match the DEV system. The real deposition pressures become identical, and the optical gap becomes identical. Yet the Raman and HFS results show a better match with similar flows (dissimilar pressures). The Raman results must be impacted by something other than pressure. Many authors state that substrate bias is the most important determinant of film characteristics. Kasper[64] is one of these. He gives what he considers to be a robust method for calculating the voltage drop across the anode sheath. Kasper states that the anode drop is comprised of two voltages:

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[64] Kasper,W., Bohm, H. and Hirschauer, B.; "The influence of electrode areas on radio frequency glow discharge"; Journal of Applied Physics; 71 (9) 4168; May 1992.

1) a portion from RF self biasing and
2) a portion from the difference between electron mobility and ion mobility.

The first is driven by the anode/cathode ratio, the second by the electron temperature. An argument can be made that despite their differences, the two systems have very similar anode sheath voltage drops. Kasper's equations support this hypothesis. The MAN has more grounded shielding, thus raising the anode/cathode ratio. But the DEV is operating at half the MAN's pressure, so the Udc is higher due to the higher electron temperature. If some reasonable assumptions are made about the area wetted by the plasma, the anode drop is calculated to be about 80 volts in both systems. The assumptions made in the calculations below are:

1) The DEV plasma wets one-quarter of the pallet and a corresponding arc of the side wall.
2) The MAN plasma wets a similar geometry and the sides of the deposition can and the deposition shaping shields, which cover half the can area.
3) The electron temperature is inversely proportional to pressure and the DEV gives a Udc of 20 volts. (Normal range is given as 6 to 20 in Kasper).

Note that the dimension of the target is the same in each system.

Anode sheath voltage drop calcuations

$R_{DEV} :=$ Radius of the development table

$R_{MAN} :=$ Radius of the manufacturing table

$Usb_{DEV} :=$ Self bias of the development system

$Usb_{MAN} :=$ Self bias of the manufacturing system

$Udc_{DEV} := 20$

$Udc_{MAN} := .5 \cdot Udc_{DEV}$

$A_c =$ area of the cathode

$A_{DEV} :=$ Area of 1/4 of the table + Area of the corresponding arc of chamber wall

$A_{MAN} :=$ Area of 1/4 of the table + Area of the pie can + Area of uuniformity shields

$$Ua_{DEV} := \frac{Usb_{DEV}}{\left(\frac{A_{DEV}}{A_c}\right)^2 - 1} + Udc_{DEV}$$

$$Ua_{MAN} := \frac{Usb_{MAN}}{\left(\frac{A_{MAN}}{A_c}\right)^2 - 1} + Udc_{MAN}$$

$Ua_{DEV} = 80$

$Ua_{MAN} = 79$

Friction, Stiction, CSS, and breakdown were comparable between the systems

Heads coated in the MAN system and heads coated in the DEV system were compared in a combined CSS, Friction and Stiction test. A second set of heads were compared through breakdown voltage tests. The results matched. All heads tested passed 100K cycles of CSS testing[65]. The groups from the two systems had no statistically significant differences in friction, stiction or breakdown voltage. Heads coated in either system thus perform identically when inserted into a drive.

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[65] O'Brien, Kevin, Internal Document, January 1995.

3) How thin can the film can be?

Work toward thinning the protective layer was underway even as the transfer of the film from development to manufacturing proceeded. The areal density penalty of even a thin film was cause for concern. A portion of this thesis is devoted to investigating how thin the film might be and still function.

Experimental:
Single crystalline silicon substrates were coated with the standard underlayer of amorphous silicon followed by various thicknesses of overcoat. The Terksville MAN sputtering system was used. The ten runs comprising the experiment were accomplished in two days. They were randomized to avoid introducing any time dependent trends.

The sputtering conditions were the standards developed for the MAN system. Overcoat thickness was varied by changing the deposition time. Conversions from deposition time to thickness were made assuming a constant deposition rate.

The area tested was the center two inches of a four inch substrate. Thickness variation in this region has been previously characterized to be less than one percent. Three deionized water drops were placed on the samples and were measured using a goniometer within five minutes of unloading from the sputtering system. The drops were remeasured at intervals up to 30 minutes. Individual goniometer readings are repeatable to within one-half a degree.

Results:
The results are summarized in Figures 37 and 38. Figure 37, "Time behavior of goniometer readings", tracks the change in measurement of two drops with time. The angle decreases with time.

Because of the dynamic nature of the measurement, Figure 38, "Goniometer Analysis of Overcoat Surface", shows three traces. The first trace is the average of the first measurements of the left and right edges of the center drop of water. This drop was the first drop measured on each sample. The second trace is the average of the initial measurements on all three drops. The third trace is the center drop at 20 minutes. All three traces show similar behavior relative to the thickness of the overcoat layer.

Figure 36: Example of a bead angle

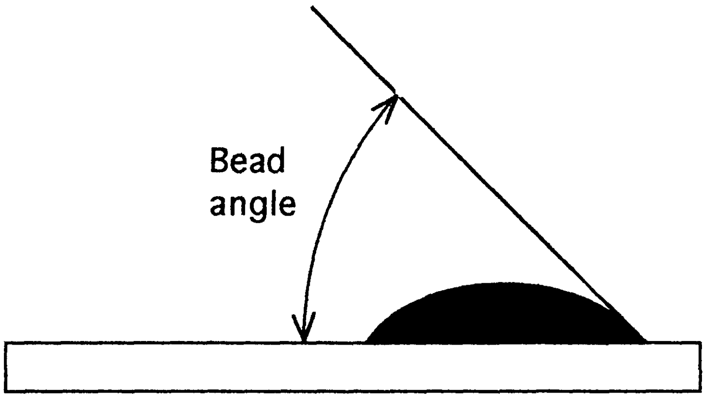


Figure 37: The goniometer reading is a function of time since drop applied

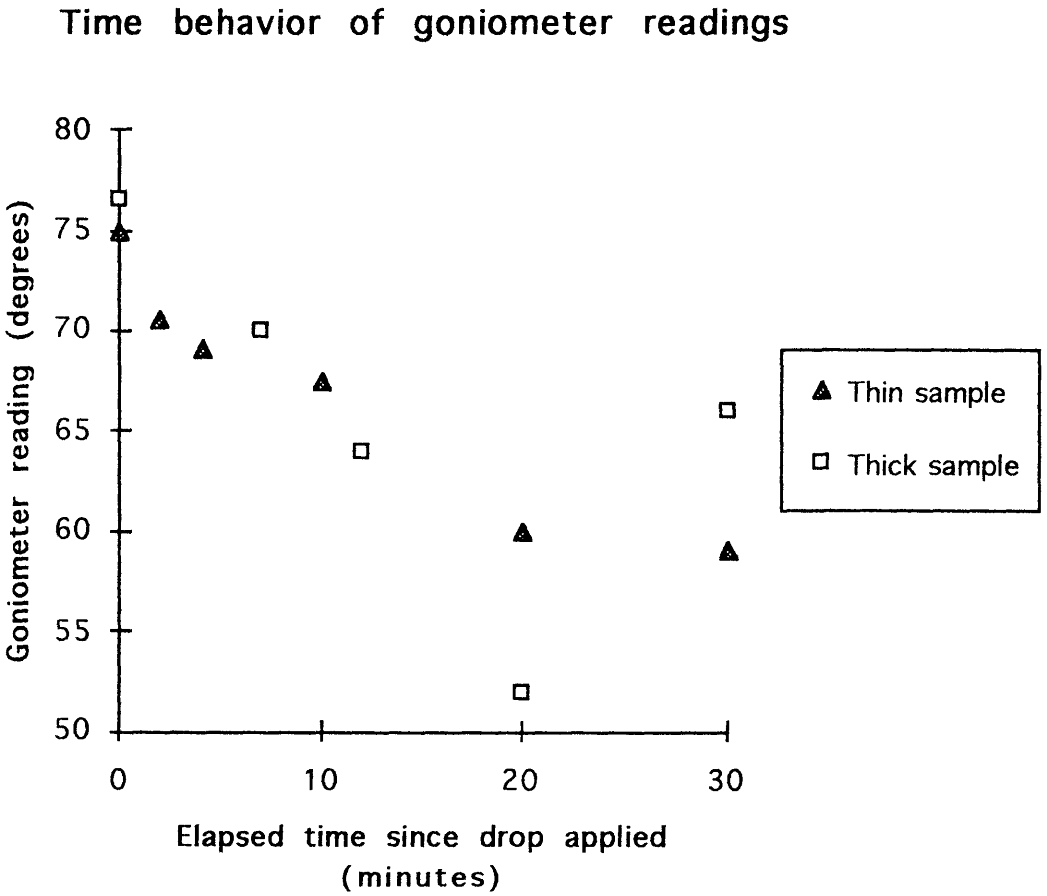
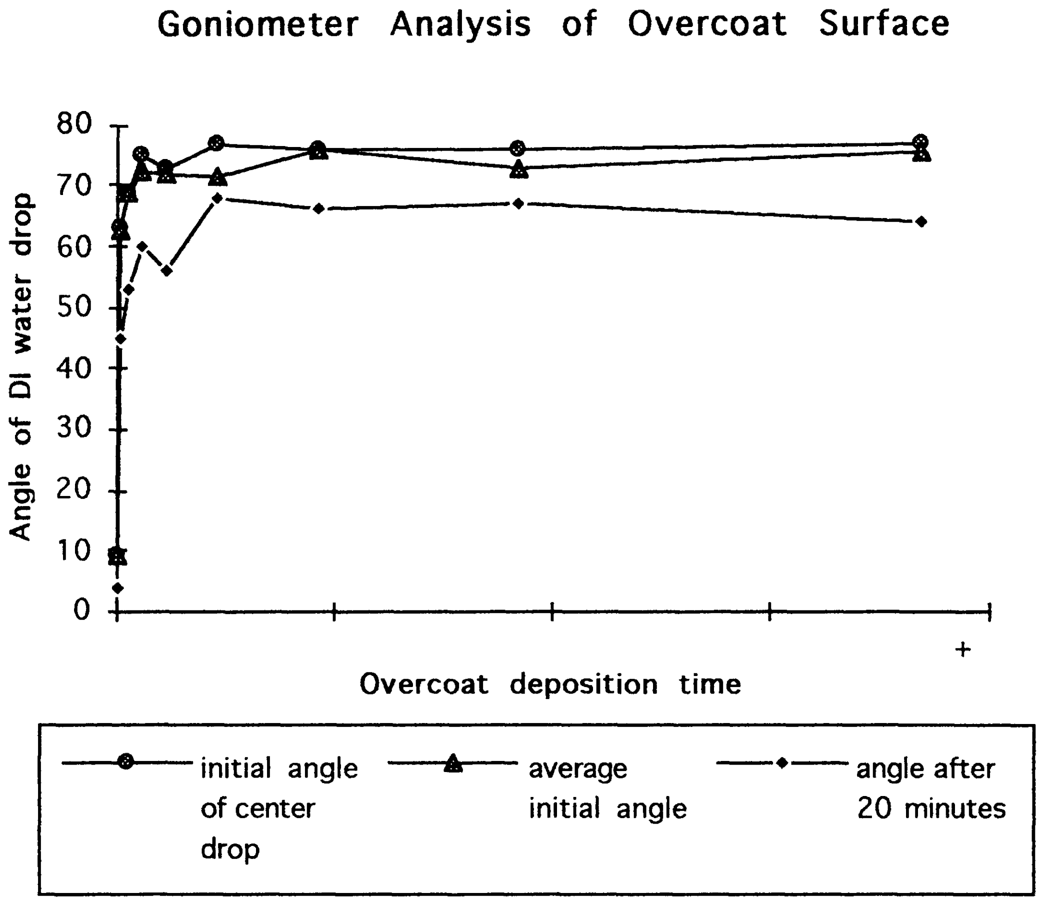


Figure 38: Surface properties change markedly at as film thickness decreases



Discussion

The time dependence of the goniometer measurement is due to two competing effects, bonding with the surface and evaporation. Complete bonding of the water drop to the surface took between 5 and 10 minutes. This is supported by the observation that a drop placed on the surface easily rolls off after 1 minute, but does not roll off at all after 10 minutes, even with the wafer perpendicular to the ground or upside down. The contest between evaporation and surface bonding was observed on the 40 angstrom sample. At 12 and 20 minutes the normally convex point of contact became concave as the surface bonding held to the original dimensions of the drop while evaporation reduced the drop volume. At 30 minutes, the diameter of the drop had lessened and the point of contact was convex again.

The underlayer, amorphous silicon, oxidizes rapidly in the ambient when it is removed from the sputtering system for measurement. This oxidized silicon surface is hydrophilic and gives a very low angle drop (9 degrees). Less than one angstrom of overcoat changed the surface properties markedly. The bead angle continued to increase up with overcoat film thicknesses up to a threshold thickness, after which the bead angle remained constant.

This suggests that the surface properties of the overcoat films thicker than the threshold value are much the same. This does not imply that a film just over the threshold would provide the same lifetime as a thicker film; thicker films should wear longer. But based on this, one expects the interface behavior to change on films thinner than the threshold. It is probable that this threshold thickness marks the transition from island growth to a continuous film.

AFM surface roughness

Samples from the thickness matrix were observed using AFM. Samples of the bare substrate, samples of the substrate coated with amorphous silicon and samples of the substrate coated with both the silicon and various thicknesses of overcoat were analyzed. The only quantified data to emerge from this study was surface roughness. The surface roughness of the samples changes somewhere between twice and four times the threshold value measured above. The 2x sample has the same roughness as every thinner sample and as the substrate. The 4x sample is significantly different. The AFM work was done in random order on two consecutive days. Multiple samples and multiple traces per sample were collected at each thickness. The graph of surface roughness is presented in Figure 39. Ra is the average range of the surface profile -- the average distance from peak to valley.

A similar plot was made for lateral force measurements on the AFM probe. It is presented as Figure 40. Lateral force changes as different surfaces, with different amounts of drag, are traversed by the needle. The 4x sample was thus predicted to give a lower lateral force range than the 0.25x sample. At 0.25x, the surface film should have been in island growth. Two species, the undercoat and the overcoat, should be visible to the needle. At 4x, the surface film is expected to be continuous. The lateral force measurement did not behave as predicted. The difference between 0.25x and 4x went opposite the expected direction. Little information beyond the average surface roughness was obtained using AFM to characterize these surfaces.

Figure 38: Surface roughness of the protective coating does not change until several times the threshold thickness is deposited

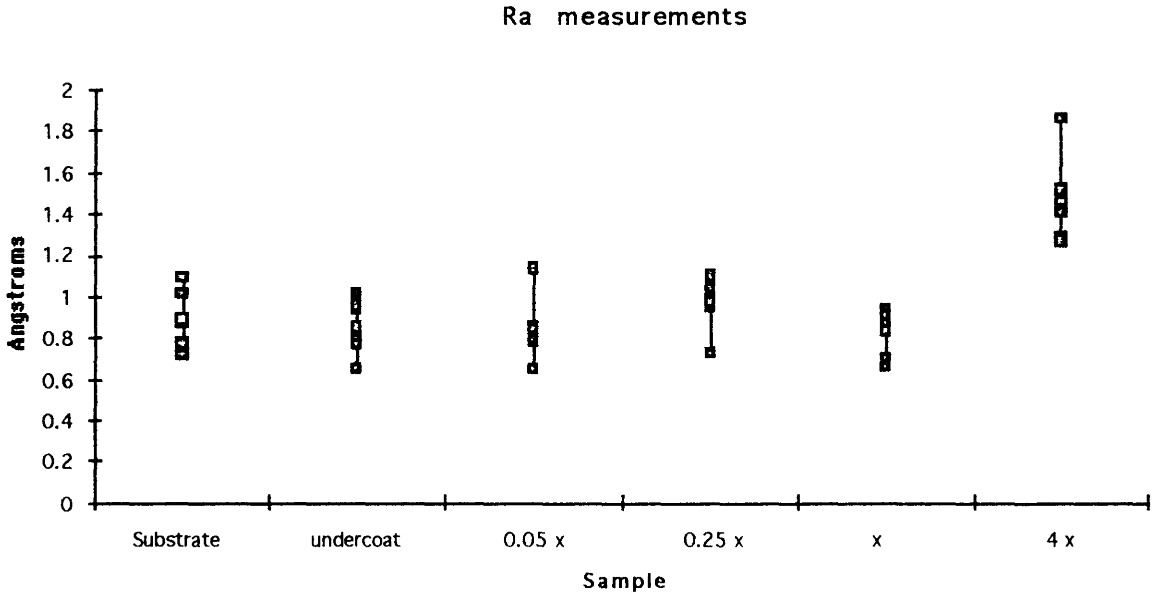
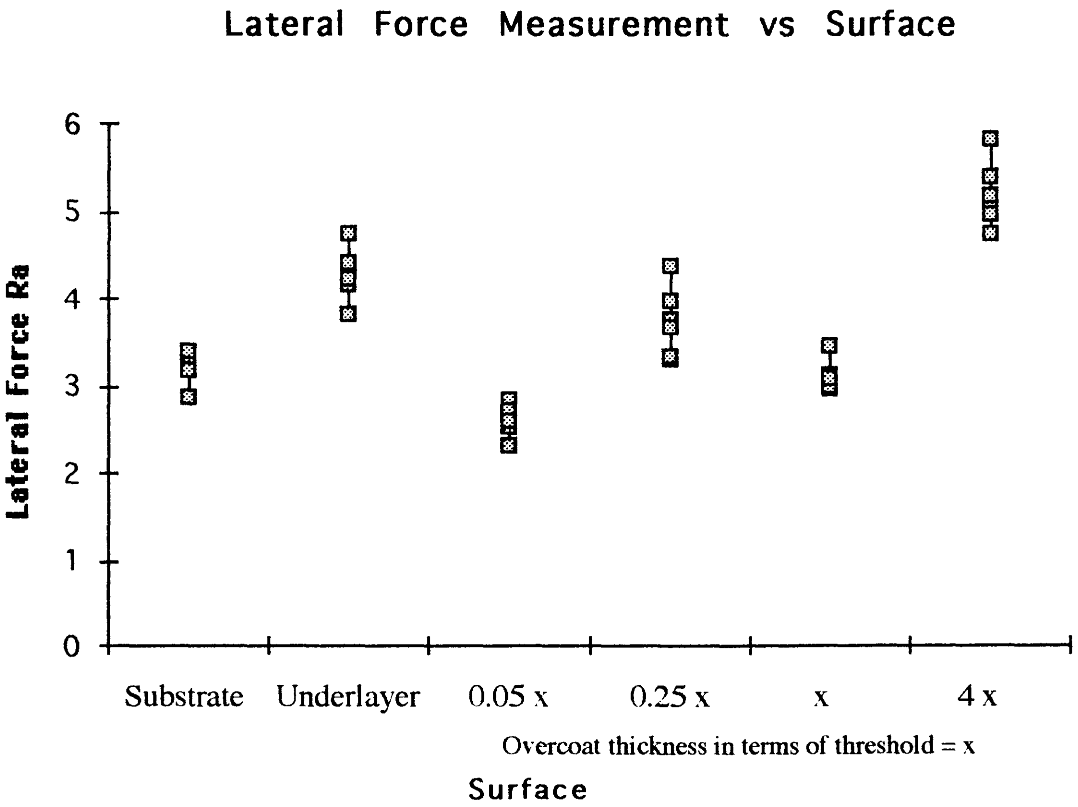


Figure 39: The average range of lateral force measurements as a function of surface



Discussion of Experiments

Results vs. Literature

In his article on calculating sheath voltages, Kasper[66], calls out several films sensitive to the voltage drop across the substrate sheath. Amorphous carbon is one of these. According to theory, substrate ion bombardment will preferentially break sp^2 bonds, thus giving a film with a higher sp^3 content. Adding bias to the substrate should therefore enhance the sp^3 content of the film. Looking at the FTIR data in Figure 17, there is more area under the sp^3 peaks for the biased run than for the unbiased run. This experimental result matches the literature.

The FTIR results from this study showed nearly identical traces with the exception of the 25% reactive component source gas. It was the only sample to show sp^2 signatures in the FTIR spectra, notably the peak at 1579 resulting from the C-C stretch of aromatic carbon. None of the samples showed any of the sp^2 C-H stretching bands between 2950 and 3050 reported by Dischler, even though Raman results show that there is significant sp^2 bonding in these films. The FTIR used must be more sensitive to sp^3 than to sp^2 bonding in these films.

Vossen and Kern[67] state that the two factors most affecting gas incorporation in a sputtered film are pressure and deposition rate. As deposition rate goes up, the ratio between sputtered atom arrival rate and incident gas arrival rate changes. As pressure drops the plasma potential increases, accelerating more gas ions toward the substrate. Evidence to support both of these mechanisms was observed.

Based on the HFS data collected on the 2^{5-1} experiment, the deposition rate is the dominant effect in the DEV system (Figure 20). At the highest power used in the experiment, a pressure effect was seen (Figure 22). Under this high power condition, a low pressure in the chamber gave less hydrogen to the film than did a high pressure. This result reinforces the arrival rate predominance in the DEV system.

The MAN system behaved differently relative to pressure. More H was incorporated into the film at lower flowrates. Lower flowrates with a constant pressure at the pump throat translate into lower pressures in the deposition region. So in the MAN system H incorporation follows the pressure effect on plasma potential.

Lee and Smallen[68] report a strong correlation between initial DI water bead angle and atomic % H in the film. Comparing the bead angles of these films against their results indicates that our film has an H percentage very near to 53%. Lee and Smallen obtained their best wear results with a film containing this atomic percent hydrogen.

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[66] Kasper,W., Bohm, H. and Hirschauer, B.; "The influence of electrode areas on radio frequency glow discharge"; Journal of Applied Physics; 71 (9) 4168; May 1992.

[67] Vossen, J. L. and Kern, W.; Thin Film Processes; Academic Press;1978

[68] Lee, J. K., Smallen M., Enguero, J., Lee, H.J. and Chao A.; The Effect of Chemical and Surface Properties of H: Carbon overcoats on the Tribological Performance of Rigid Disk Media; IEEE Trans. Magn. 29:1 (1993).

Raman spectroscopy clearly shows the G (graphite) band and the D (defect) bands that the literature reports. Comparing these Raman results to those reported by Ager[69], these films fall into the long-wearing, abrasion resistant domain. This is based both on the downward shift in the location of the G peak and on the low Id/Ig ratios. Note that Ager's work only extends down to an Id/Ig of 1. Ager's Raman instrument can measure films less than 100 angstroms thick. The lab where this Raman work was done could not. The low Id/Ig ratios of 0.2 to 0.6 could be partly due to a lack of resolution in the lab's detector. Both Ager's and Yoshikawa's Raman work on similar films appear to have a higher signal to noise ratio.

The amorphous hydrogenated carbon films produced and measured in this thesis follow the results for similar films reported in the literature. With increasing reactive fraction in the sputtering source gas:

1) Total hydrogen content remains relatively constant
2) Bonding shows a higher proportion of sp^2
3) Optical gap decreases

With increasing substrate bias

1) Deposition rates decrease
2) FTIR indicates a greater amount of sp^3 bonding

CSS testing confirms that these films have the long wearing characteristics that the literature predicts for films with these Id/Ig ratios, G peak positions, and DI water bead angle.

System Matching

It is important to note that the response surface mapping found no reason to deviate from the recipe developed by the development group. Their film turned out to be robust enough to transfer to a different sputtering tool without modification. Differences were observed, but they had no significant effect on drive performance.

The biggest difference between the systems is the pie shielding on the MAN machine. This causes the real deposition pressure to be higher than the indicated pressure. With gas flowrates matched the MAN system is operating at nearly twice the pressure of the DEV machine. The company decided that improvement in thickness uniformity and breakdown voltage variance was more important than the difference in optical gap caused by running at similar flows.

FTIR work shows that the MAN system has slightly more C-H bonding under these conditions. HFS shows that the MAN also has more total hydrogen in the film. The total hydrogen content appears to be driven by power in the DEV system and by pressure in the MAN system.

Raman results for the two systems were quite similar despite these differences. This is attributed to the calculated anode sheath voltage drop being the same in both systems. Films run in either system are thus bombarded with similarly energetic ions during deposition.

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[69] Ager, Joel, III; Optical Characterization of Sputtered Carbon Films; IEEE Trans Magnetics; 29 (1); 1-93; 259

Implications for Process Control

Differences in drive-level friction and stiction due to changes in sputtering system inputs are just visible above the noise with the 30% to 75% swings used in this experiment. Within the normal control capability of modern sputtering systems, chances are remote that deposition variance will be visible at the drive level. This is good news for the operation of the sputtering cell. Small changes in deposition parameters are not likely to impact the functionality of this tri-layer film.

The most important control factors in the sputtering system are:

1) Anode sheath voltage drop
2) Partial pressure of reactive gas in the deposition region

Other deposition inputs have much less effect on the performance of the resulting film. Of course, other inputs combine to determine the plasma characteristics, which in turn determines the anode voltage drop.

The most productive (ability to see film changes vs. input effort) film measurement system used in the course of this work was the UV-Visible spectrophotometer. It provides quick post-deposition feedback and is relatively easy for an operator to use. Its ability to monitor the entire film stack at once makes it a good process control tool. But the UV-Visible spectrophotometer alone is not sufficient.

The FTIR found bonding differences between the 9% and 25% source gas runs, while the UV-Visible readings were nearly the same. A second example is found in the FTIR changes over time in the DEV sputtering system. The 2^{5-1} experimental matrix showed that most splits were clustered very close together. The time-delayed sample stood apart, showing much less sp^3 bonding than the others. It was sputtered some 3 months later. Throughout this period, the optical gap in the DEV system stayed within specification.

Robertson's film modeling[70] shows that the optical gap is controlled by the size of the sp^2 regions, whereas the mechanical properties of the film are determined by the nature of the bonding between these regions. The optical gap alone is thus not sufficient to predict the functionality of the film.

It is recommended that Raman or goniometer measurements be made periodically to ensure the deposition tool is not drifting. Provided samples can be measured at the same time post-sputtering, the goniometer was the second most productive method of monitoring the film. Goniometry shows differences in hydrogen incorporation and may detect differences in bonding. The drawback is that it is sensitive to technique and may not be able to be used in production. Ager has correlated Raman spectra to film wear characteristics. Lee and Smallen[71] have linked goniometry with %H and %H with CSS lifetimes.

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[70] Robertson, J. ; "Mechanical Properties and Coordinations of Amorphous Carbons"; Physical Review Letters; Vol 68 (2); 1992

[71] Lee, J. K., Smallen M., Enguero, J., Lee, H.J. and Chao A.; The Effect of Chemical and Surface Properties of H: Carbon overcoats on the Tribological Performance of Rigid Disk Media; IEEE Trans. Magn. 29:1 (1993).

It is also recommended that the stiction regression results be kept in mind when monitoring the sputtering system. This work shows that a subsurface film can have as big an impact on drive level performance as can a surface film.

Implications for Future Development

Future film development is likely to move toward thinner films to reduce the magnetic spacing between the head and the disk. A large change in film surface properties was observed when the overcoat film thickness drops below a threshold value. It is likely that there is a fundamental barrier to reducing film thickness at that point.

The work done in this paper shows that increasing the reactive component in the source gas is an easy way to change the characteristics of the slider coating. As the reactive component goes up the film will have a greater proportion of sp^2 bonds. Eventually it will become polymeric. This will make the film softer. It might be advantageous to change the head coating to optimize it to different disks coatings.

This thesis found that, for this tri-layer system, sputtering deposition parametric control is not a primary source of friction variance in the drive. To be able to optimize the head coatings to particular disk characteristics will require that the other sources of variation be found and removed. Otherwise, they obscure the effect of sputtering parameters. Large sample sizes can compensate for the noise in the friction measurements, but the experiments become very slow and very expensive.

Recommendations for Further Work

As drives evolve, more attention will need to be paid to environmental influences. Work like optimizing heads to disks must proceed taking into account fluctuating environmental factors. Such factors were not considered in this work. Improving the robustness of the head disk interface in the face of environmental changes could create a competitive advantage. The learning acquired through such an attempt would be valuable in increasing drive lifetimes in any event.

Odds are good that a faster deposition could be developed. Power did not show up as a particularly significant input in the MAN system. A shorter deposition could be developed if throughput at the station were ever constrained.

The results of regression show that friction after 24 hours of drag changes less than 2% due to large changes in pressure, bias and silicon thickness. The friction effect of the tri-layer film was very robust. The breakdown voltage swung much further - 50% - as a result of input parameters. This suggests that the film could be modified to provide greater ESD protection without sacrificing much friction reduction.

A more systematic study of the effects of film bias needs to be made if bias is ever to be used to change the film structure. The MAN system's ability to independently bias the table lends itself to such work. This thesis mirrors the literature in finding lower deposition rates and more sp^3 character with bias, but does not identify an optimum bias setting.

4) Changes in manufacturing practice were necessary to increase the throughput.

Handling benefited from early manufacturing involvement
Because the new machine had just been ordered and the fixturing had not been designed, there was an opportunity to involve manufacturing in the development of the parts handling system. As mentioned earlier, the development site spent a high proportion of their operator time handling the product before and after the sputtering operation. The sputtering fixtures were ceramic, and they were designed such that manual handling of each head was required. The parts were:

Inspected
Cleaned as required, one at a time
Loaded one by one into the sputtering fixture
Placed into the sputtering system
Sputtered upon
Removed from the sputtering system
Unloaded, one at a time from the sputtering fixture
Inspected
Cleaned as required, one at a time

Engineering at the manufacturing site proposed a fixture that would allow hundreds of parts to be transferred in one step. In order to collect manufacturing input on the system, a cardboard mockup of the proposal was made. This facilitated the conversation with manufacturing because it eliminated the need to examine and explain blueprints. The mockup was left in the area for two days. Supervisors passed on the request for input, and engineering came in on every shift to interview operators directly.

Over twenty suggestions were collected. Subsequent conversations with the manufacturing people who made the suggestions coalesced them into four. These were designed in to the equipment. The suggestions were simple, logical changes based on the operator's long experience in handling heads.

Operators were somewhat shocked at being asked their opinion before the equipment had arrived. But the mockup allowed them to visualize the handling requirements and make suggestions. These suggestions, in combination with the improvements in cleanliness discussed below, allowed us to cut the labor content of the operation dramatically. Because the operator inputs were incorporated, part handling was intuitive for them and they required very little training.

Cleanliness improved because of a firm commitment and lots of teamwork
The parts are inspected and cleaned twice in the process flow practiced in the development site. These steps were necessary to remove particulate that accumulated on the head surface. Particles are detrimental for three reasons. First, they mask areas of the substrate from receiving deposition. Second, they can interfere with proper film adhesion. Third, they can impair the flying characteristics of the head or otherwise contaminate the head disk interface.

The manufacturing site made a decision well before the new machine arrived that these inspection and cleaning steps could not be allowed if the process were to remain cost effective. Both engineering management and manufacturing management supported this stand. To eliminate these steps the following were emphasized:

1) The parts had to be so consistently clean coming from the preceding operation that no inspection would be required.

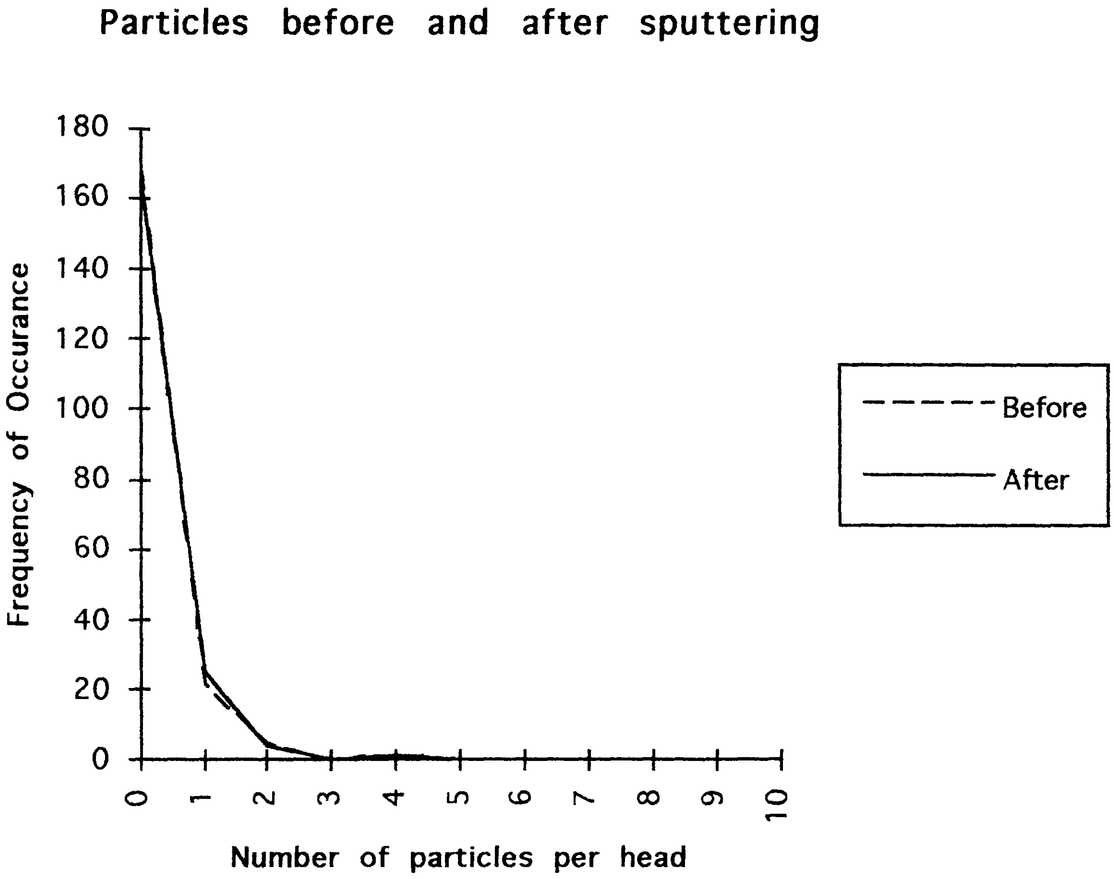
2) The parts had to stay clean throughout the sputtering operation.

The upstream engineers accepted this challenge and worked closely with us through the process transfer to improve the output of their operation. The sputtering system was set up in the area's first clean room, as was the final clean operation of the preceding operation. Tight control was maintained over the sputtering fixturing. This achieved goal number two.

There was some engineering dissent over the handling process that was developed with manufacturing input. Some of the upstream engineers felt that the bulk handling system would add contamination. They were pushing for an automated, single head solution. To quell their arguments, data was generated by mapping particle additions through the sputtering process. This proved that sputtering only highlighted incoming particles and added few of its own. This is graphed in Figure 41. The lines representing before and after particle levels almost overlay. Particles added in sputtering, while not zero, are negligible compared to particles incoming to sputtering.

Once this information was disseminated, the upstream operation redoubled their efforts to supply clean product. Teamwork grew stronger. Involvement of the operators in the results of the cleaning work heightened their sensitivity to the issue. The added attention of everyone in the area achieved goal number one. Only a small sample inspection is done after the sputtering operation.

Figure 41: **Sputtering had a small contribution relative to incoming contaminants.**



The early start on the new fixturing turned out to be justified. The ensuing fixture development and manufacturing work took longer than the process characterization and became the key item on the critical path.

These changes were so successful in reducing operator labor that the development site began using our fixturing in their equipment.

Reasons this transfer was successful

The transfer of this process step from the development site to the manufacturing site worked well because of three factors:

1) The development engineer stayed with the process throughout the first year of manufacturing and throughout the transfer.

He was involved with the MAN from the decision to purchase it until the transfer was complete. He participated in design and execution of the experiments in this thesis. Manufacturing engineers went to his site to run experiments on his system well before the MAN system was shipped. The development engineer went to the MAN factory for system acceptance testing. His willing participation gave the transfer the momentum necessary for success.

2) Manufacturing input was collected before the system design was finished.
This allowed their ideas to be incorporated into the system without expensive retooling. The fact that the system arrived with their thoughts incorporated accelerated their acceptance of the change. The implementation of the operator's ideas led to a 100% reduction in system labor content.

3) The upstream engineering group enthusiastically joined in the effort to reduce particles.
Their participation cemented the mindset changes necessary for effective particulate control and process integration.

Moving the operation to a clean room and enforcing cleanroom discipline provided graphic proof to the operators that change was required to be successful. It wasn't merely a "clean it up where it stands" operation. The result of the upstream participation and the change in manufacturing mindset was another labor savings -- reduced need for visual inspection.

5) Effects of the Takeovers

Introduction

Two years ago, the giant Frammis Corporation (FRM) purchased a division of Fine Grain Incorporated to obtain a new technology. Transfer of this new technology from the acquired division to FRM has not gone as smoothly as planned. In the midst of this technology transfer, Stormore Corporation bought the FRM division which had bought the Fine Grain division. This section examines the culture of the Fine Grain and FRM divisions and the management of the technology transfer. It then examines Stormore's takeover of the two units. Using recent literature on empowerment, change, and technology transfer as a basis, recommendations to Stormore's management on how the situation might be improved are given.

History

August 31, 1992 -- Electronic News Publishing

"Fine Grain Limited, faced with the prospect of shutting or selling its thin film drive head operation, has opted to hand over the unit's fate to Frammis Corporation . . . . . Fine Grain receives a 19 percent interest in a joint venture [named UltraMagnetics Inc. or UMI] and a promise by FRM to invest up to $50 million to continue development and bring to market the magneto-resistive thin-film head technology Fine Grain had been developing.

Sources close to FRM said Fine Grain was much further along in developing magneto-resistive heads than FRM's own storage unit, which was only in the advanced R&D stage on MR technology. . . . FRM's program was not seen as 'a serious program or one that was close to fruition.'

Even with the earlier access to MR heads via the joint venture, the sources indicate that FRM doesn't plan to use that technology in any drives for at least another year. In the 3.5 inch form factor the company expects to be able to build several more generations of drives -- going well above the 2 GB level with its current inductive heads."

October 27, 1992 -- Business Wire

"Two months after the announcement of its establishment, UltraMagnetics Inc. of Harrisburg, Virginia., announced the first shipment of fully functional 50 percent magnetoresistive heads to disk drive manufacturers."

July 6, 1994 - The New York Times

"After months of speculation that it would begin to sell off parts of its business, the Frammis Corporation said yesterday that it was negotiating the sale of part of its storage business to the Stormore Corporation, a maker of disk drives. . . . .

Stormore, the fast-growing market leader in disk drives, has focused on building hard drives for personal computers. . . . . Stormore, which holds more than 21 percent of the market, had been a small player in the high end of the disk drive market, which caters to powerful servers and midrange computers. Frammis has less than 1 percent of the disk drive business but is well regarded in the high end of the market. . . .

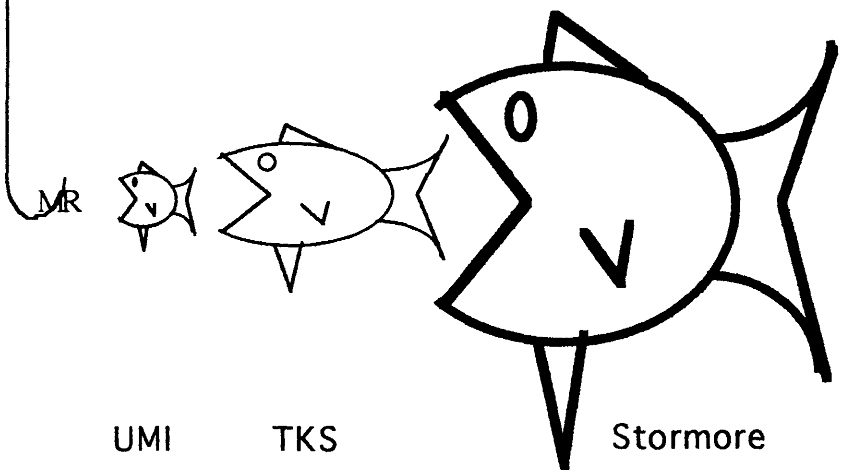
Frammis had developed new recording-head technology called magneto-resistive, or MR heads through an investment in UltraMagnetics, a joint venture with Fine Grain Limited. . . . This [MR] technology is difficult to develop and Stormore hasn't gotten there yet, so this would be appealing to them."

July 20, 1994 -- The New York Times
". . . [Frammis'] disk storage business, though not profitable, had quintupled in terms of production within the past 12 months.

July 20, 1994 -- The Denver Post
"Frammis' disk-drive business, revamped over the past few years, is rated as one of the company's best run operations. The storage unit. . . generated an estimated $1 billion in fiscal 1993.

October 3, 1994 -- Business Wire
"Frammis Corporation today announced the completion of the sale of Frammis' magnetic disk drive, tape drive, solid state disk, and thin-film heads businesses to Stormore Corporation for $360 million. . . ."

Figure 42: A graphic representation of the takeovers



Culture of the FRM Slider Engineering Group

The FRM slider engineering group employs 50 people. The Thin Film Heads Division of which Slider engineering is a part is located in Terksville in the middle of Massachusetts, approximately 75 minutes from downtown Boston. The division assumed the name of the town where it is located, Terksville, abbreviated TKS.

The Thin Film Heads division has been in existence within FRM for more than 10 years. It has been one of Frammis' more successful divisions in recent history as evidenced by the fact that it has grown rapidly in both employees and output. Though it is still "not consistently profitable", the division brings in a cash flow of roughly $1 billion per year.

The culture of the Thin Film Heads group is a mixture of their FRM legacy and of their success. They are burdened with large bureaucracies and very tight cost control.

Examples:

Shipping: It takes a cost center manager's signature on a six-carbon-copy form to get material shipped to another site.

Office Supplies: Many engineers began to bring in their own office supplies. It was virtually impossible to get a role of transparent tape or a pair of scissors because stationary supplies were one of the first targets in the belt tightening that eventually led to the sale of the Disk Drive Group to Stormore.

Security: FRM has a state-of-the-art security system. A cost center manager's signature on a triplicate form is required to gain access to areas on a room by room basis. Roughly two weeks are required for security clearances to be implemented.

On the other hand, FRM can move very rapidly in response to changing business conditions. They have quintupled manufacturing output in the last year. The disk group is one of the few places within FRM which received any significant capital for expansion during the downturn. In an interesting contrast to the scarcity of transparent tape, $2200 was released for a trip to UMI to enable this study.

Organization:

Slider engineering supports both development and manufacturing. Manufacturing support and Development used to be separate engineering groups but merged 18 months ago. The engineering group has done an excellent job of blending manufacturing and development. The disk drive industry is on a very steep learning curve. The FRM engineering group has generated numerous patents and patent applications while at the same time supporting the explosive growth in manufacturing output and the rapidly changing technology. There is, however, a downside to combining the groups. The merger of the manufacturing and development engineering groups, combined with a lack of capital to fund new research, has accelerated a slow drift in focus away from R&D and towards manufacturing support.

FRM has a culture of give-an-engineer-a-job-and-check-back-when-it-is-supposed-to-be-done. This gives the engineers a great deal of freedom, which most enjoy. There is a corresponding problem of projects stretching out beyond their planned completion dates.

The engineers within the slider portion of the thin-film head group of FRM seem to view the organization as family. They are a tightly knit, very cohesive group. Work and social life are interwoven for a large proportion of the engineering team. They socialize in the course of working while in the plant, and work while in the process of socializing outside the plant.

The majority of engineers in the slider group view the merger with Stormore as salvation from the long, slow slide of Frammis. They are glad that Stormore is taking over. The hope is that capital will flow more freely and that Stormore will address and resolve issues they perceive management at Frammis has ignored.

High on their list of ignored issues is the feeling that the slider groups at UMI and TKS are moving in different directions. The slider group at TKS feels that the slider group at UMI needs a huge boost in manufacturing capability; that the process as developed by UMI is not suited for high volume manufacturing.

Nor are the TKS slider engineers completely happy with manufacturing in TKS. The engineers feel that manufacturing is single minded in its pursuit of numbers, even to the point where quality is compromised. The engineers feel that manufacturing is simplistic and behind the times in understanding of manufacturing paradigms and research. The feeling is that most of the manufacturing leadership is from a bygone manufacturing age.

Culture of UltraMagnetics Incorporated

The Slider engineering group of UMI also employs about 50 people. UMI is located in Harrisburg Virginia, which is 15 minutes outside of Lynchburg and about 40 minutes from downtown Richmond. It is housed in one-half of a Fine Grain building on the main Fine Grain campus. The delineation within the building between Fine Grain and UMI is a change in the floor covering from carpeting to linoleum.

UMI was established in August 1992 as a joint venture between FRM and Storage Technology with FRM the larger partner in an 81/19 split. At that time, only UMI and IBM had viable MR head technologies.

The culture of UMI is very much like that of a venture capital startup. The majority of the engineers are young and aggressive. Communication flows freely within the comparatively small company. There is little encumbering bureaucracy. When acquired by FRM, the entire UMI organization had only 250 people. That has since grown to 500 people; still small in comparison with the FRM Disk Group's 5000. Described below are the same three cultural artifacts described above. This will facilitate comparison between TKS and UMI.

Examples:

Shipping: Shipping at UMI involves writing the address on a scrap of paper and delivering the address and goods to be shipped to the shipping department. No signatures or duplicate copies are required.

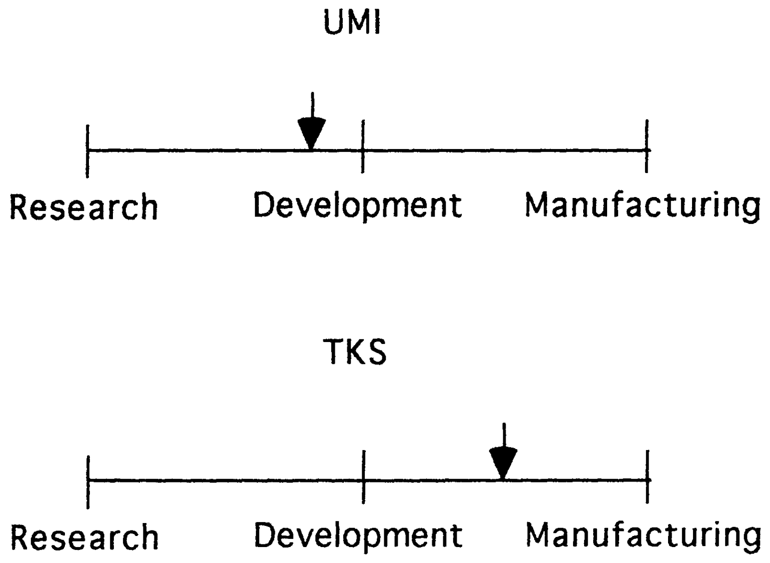
Office supplies: Miscellaneous equipment and supplies required to get the job done are readily available. Everyone bends over backward to help visiting engineers be successful in their task.

Security: UMI uses security system hardware similar to that at TKS. The supporting authorization system is much faster: 10 minutes compared to 14 days.

Organization:

Like the slider group at FRM, the engineers at UMI are responsible for all aspects of research, development and manufacturing. Overall, the organization is skewed to the R&D side. See Figure 43 for a comparison of where the organizations fall on a continuum. UMI runs pilot-plant production volumes as opposed to the large scale manufacturing done in TKS.

Figure 43 **Continuum comparison.**



The UMI group is proud of their ability to deliver new product and processes. In one spare office there hangs a framed note from the Applications manager to the engineering group, congratulating them on completing an 18 month long pole trimming development project one week ahead of the original schedule. This meshes with the fact that UMI fulfilled its MR obligations on time and with good results.

Some in TKS scoff at the on-time performance of UMI, citing slips in agreed-upon changes in their process to make the UMI and TKS processes more similar. Based on the researcher's three months in TKS and 10 days in UMI, UMI places a greater emphasis on planning and delivery. The engineers in UMI don't appear to have the same latitude enjoyed by engineers in TKS. Their work is more directed by management than is the work in TKS.

This researcher wasn't in UMI long enough to get a solid feeling for how the organization is viewed by its employees. There is a bit of feeling that it was an avenue to excel, a place to make one's mark and build a career.

The merger with Stormore was viewed in a more jaded manner -- "We've been through this before, this is nothing new, perhaps there will be more capital," was the feeling. There was a second feeling that Stormore really purchased the group for UMI's MR technology, and that had UMI been available as a stand-alone entity, perhaps FRM's Disk Drive Group would still belong to FRM.

Manufacturing, at least large-volume manufacturing, is still somewhat new to the slider engineers at UMI. The view of it is somewhere between "its a necessary function to get our product to market" and "its a distraction from my development duties". Many in the group wish that manufacturing would manufacture and quit calling on them for assistance.

Relationship between the two sites
TKS and UMI each view themselves as the technological leader. Both organizations are very proud of what they've accomplished. TKS has core competencies in laser machining, grinding/lapping, and air bearing design. They support a manufacturing output ten times greater than UMI with a similar number of engineers.

UMI is an industry leader in developing MR technology in support of the next generation of disk drives. They know that FRM bought them because its own MR research and development effort "was not close to fruition".

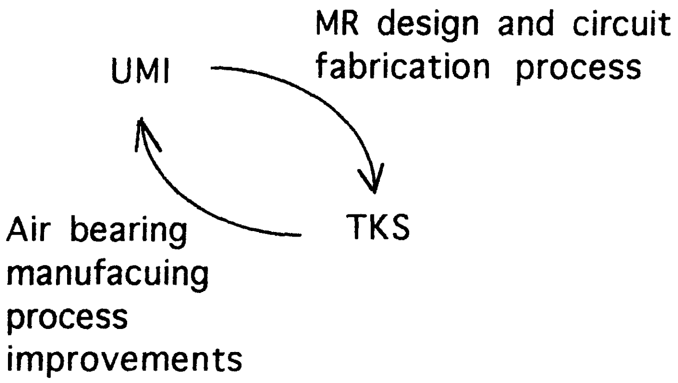
So there is a young, freewheeling culture placed together with a much older, more bureaucratic culture. One is biased toward R&D and the other is biased toward manufacturing. The success of UMI in R&D is a reminder to engineers at TKS that they've moved away from the more glorified end of the continuum. The fact that TKS has a superior slider manufacturing process is equally threatening to UMI. UMI originally believed all the technology transfer was going to be one way from UMI to TKS.

Two years after FRM bought the lion's share of UMI and began a transfer of MR capability to TKS, the organizations still think of themselves, and behave as, separate companies. We/they thinking is prevalent. Not only does each feel they are technological leader, each feels the other is a technological laggard.

Rivalry runs high between the groups. Prior to Stormore, the contest centered on whose technology would carry the day. It was a given that UMI's MR technology would form the circuitry. Whose air bearing design goes on the slider was not as clear. UMI was using technology U producing design UU, and had already qualified customers on the design. TKS was using technology T, producing design TT. TT is a new design not currently sold to anyone. Technology U cannot produce design TT and technology T cannot produce design UU. The cost per unit of technology T is half that of technology U.

Stormore's purchase exacerbated the situation. Everyone wanted to look good for the new owners. Stormore retained an external consultant on head design who is an industry pioneer in design UU. The forecast for sales on design UU necessitates additional capacity. Terksville decided that they'd have to bring up technology U despite the fact is didn't match their core competencies. At the same time, TKS gained agreement that all new product would emerge on technology T, and technology U would be phased out. UMI is changing their slider line to look more like technology T, because of the manufacturing and ensuing cost efficiencies of the T process.

Figure 44: The technology transfer flows both directions



Examples Illuminating the Relationship

After the Stormore sale was announced in early July, there was much internal discussion concerning how employee benefits would change in the transfer. There was no official information from Stormore to satisfy the rising questions. An engineer went around the system and retrieved Stormore benefits information from the MIT Career Development Office. This information was distributed in TKS. The next day the engineer flew to UMI. He gave a copy of the benefits package to his host, who began to distribute it within UMI. The first person the host shared it with responded with a chagrined, "You mean Stormore distributed this in TKS before we got it here?"

While this engineer was preparing for his UMI visit, he asked if others from TKS would like to go. The reply was: "I was out there for the due diligence a year and one half ago. I saw their system then. Nothing has changed."

Another TKS engineer was asked how much time he spends talking to his counterparts in UMI each week. "About 40 nanoseconds, and that is only when there is a problem."

The manager leading the transfer effort for MR to TKS from the UMI side has never been to TKS.

An engineer in UMI first heard of an important management decision from his counterpart in TKS instead of from management. It is not clear the communication at the peer level captured management's intent.

When a process transfer from UMI to TKS was announced, the receiving engineer said, "Great. They screwed it up and now I have to fix it."

Interviews with engineers and managers at UMI revealed another side to the interface. There was a common refrain that the transfer had:

1) Not been planned and scheduled
2) Not been assigned the same priority by all in the organization.
3) Suffered from having a succession of three managers in one year.

The people interviewed had not seen a transfer PERT or Gantt with the sequence, interconnections, schedule and resources clearly identified. Statements were made that the transfer was number one in priority to those assigned to drive it, but had a much lower priority among those at the working level who needed to execute it. Clarity of priority across the various levels and jobs in the organization was seen as lacking and slowing the transfer.

Stormore Takes Over

The period between the announcement and the consummation of the sale was one of employee unrest. Nothing major, but conversations seemed to contain more scenario weaving than normal. Most of the unease was concerned with employment, salary, and benefit continuance. There was no data disseminated by Stormore to mid-level, or first level management on these points. Tenure-related benefits, such as accrued vacation and annual leave, were particularly prominent in employee's minds.

As discussed above, the sale to Stormore was coincident with the transfer of the MR process from UMI to Terksville. There were significant cultural differences between the two sites. Working relationships had been strained through most of the previous two years and the tensions of the sale to Stormore didn't make communications any easier.

On July 6 Stormore's highest level staff (the CEO and top Vice Presidents) made an appearance at the sites to be acquired and answered such questions as they could, given that the sale was not finalized. Much of the one-hour meeting was spent on two topics: One) Stating the new corporation's objectives, and Two) Reassuring employees that human capital was the force behind the acquisition. Because Stormore wanted to benefit from the knowledge contained in its new workforce, nobody would be summarily dismissed.

On October 4, members of the CEO's staff again covered all the acquired sites to show a video of the celebratory speech by the CEO, to hold a question and answer session, to clearly state Stormore's goals, and to describe its culture. The first goal was to be the industry leader. That was the reason for the acquisition. A very high level organizational chart showing the reporting structure for the acquired divisions was introduced.

The first thing the new corporation did was to schedule benefits meetings. These occurred in mid-November. They seemed to answer the bulk of people's questions. The new company had personnel people stationed on site to answer questions. Despite being two months behind the onset of unrest, the benefits meetings quelled the majority of the uneasiness floating through the cubicles. The new company had no profit sharing plan, which disturbed only a few of the more senior people.

Beyond these meetings, artifacts of the acquisition appeared slowly. One day the evacuation signs in the halls had been replaced with identical maps, but bearing the new company's name. The next week capital tracking tags stating "Property of FRM" were replaced with "Property of Stormore". Construction of new entrance signs began the day of the takeover but were not completed until the first of July.

On November 4, the vice president of technology came again to answer questions and to add detail to the new organization chart. It was announced during this presentation that the UMI site would be the Technology Development (TD) center and that the Terksville site would "be freed to focus on manufacturing". Previously, each site had done both TD and manufacturing. This created consternation among the engineers in Terksville. It was the first they'd heard about losing their TD function.

Despite the unexpected announcement of TD splitting out, nothing changed for another month. The reporting structure was the same -- everyone had the same boss as they'd had, daily routines went on as before, the social web was not perturbed -- everything was the same. Rumors began that TD wasn't going to move at all. Then a Stormore manager began attending the Terksville project review meetings.

This Stormore manager had been assigned to head the newly reorganized TD group. She made it very clear that MR TD was based in UMI and that she was in control. All new Terksville project funding required her approval.

On November 31, the CEO came to Terksville and gave another presentation. The gist of this one was: "We must work together and focus on customer satisfaction. The disk drive business is fundamentally about speed and we have all the pieces we need to be successful. We must make these pieces work together well in order to provide the fast response our market demands."

On December 7, the TD manager interrupted an engineer's presentation to ask his definition of the pronoun "We". The Terksville Engineer answered "Terksville". The manager took the opportunity to dress him down thoroughly to drive home the point that "We" meant Stormore encompassing California, Virginia and Massachusetts. People left the meeting somewhat chastised and somewhat more open to a wider point of view. The CEO's message was being driven to lower levels in the organization.

Timeline

July 5	Acquisition announced	
July 6	First management visit	
	Corporate goals	
	General questions	
October 3	Acquisition complete	
October 4	Second management visit	Benefits meetings
announced		
	Corporate goals	
November 4	Third management visit	
	Corporate goals	
	Corporate culture	
	TD split announced	
November 8-13		Benefits meetings
held		
November 18	Stormore TD manager appears in review meetings	

November 31	Fourth management visit Corporate goals Corporate culture Work together message
December 7	TD manager changes definition of "We"

The net effect of Stormore's organizational changes is a shift in the power structure from Terksville to UMI. The new engineering power base is in UMI. It's where the technology that spurred the acquisition was developed. The corporation's TD manager is based in UMI, and she influences not only TD, but through budget control, the path of manufacturing progression.

The situation was still developing at the time this thesis was written. The splitting of engineering into two groups was underway. Many perceived that TD was claiming the upper tier of engineering talent.

Discussion

This bit of organizational development has many facets. Within the framework of acquisitions lie other issues of cross-site communication and of development and manufacturing working together. These topics have been much explored in the management literature. Below, ideas from the empowerment literature will be applied to the Terksville situation. The actions of Stormore will be analyzed in light of some of the literature on change. Then the actions of Stormore will be analyzed in light of some of the literature on design and manufacturing integration. Finally, a summary of recommendations will be made on how the situation might be improved.

All the Pieces are Here

Stormore has acquired much more than MR head technology. It has acquired high volume head manufacturing capability and all the design and manufacturing knowledge contained in 5000 people. It has acquired a position in the high end of the drive market. Obviously, Stormore feels that this will enhance its competitive position. It will be able to offer a complete line of drives. It will be able to design and build its own heads, to provide a comparison to and perhaps an edge over what it buys in the open market. Stormore's large volumes will drive MR costs rapidly down the learning curve. Before these benefits can be reaped, the schism between UMI and TKS must be healed.

Making the Transfer Happen

Daniels' work[72] on "Breakthrough Systems" for engineers provides a lens through which to view this situation.

In short, Daniels maintains that an engineer needs three conditions to produce consistently high levels of performance (be empowered). The performance metric he uses is on-time completion of projects.

Condition 1: Clear expectations
Condition 2: Immediate feedback on progress against expectations
Condition 3: Access to resources to do the job

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[72] Daniels, Bill; Breakthrough Performance: Managing for Speed and Flexibility ACT Publishing 1995.

This researcher found in the course of working on one piece of the MR technology transfer and in formal interviews that there are not clear expectations on the transfer. If there were, everyone would know what priority the transfer held against other tasks. Everyone would know when the transfer was scheduled to be complete and why it was important that it be completed on time. There is little doubt that the turnover in management on this project has hampered clear dissemination of expectations.

For engineering feedback, Daniels insists that a detailed PERT or gantt of the project exist for everyone involved. The level of detail must be great enough that there is at least 4 weeks of daily activity goals and 8 weeks of weekly activity goals. It is only with such careful planning that an engineer can immediately know if he is on or behind schedule. Without this level of detail, humans consistently overestimate their progress, and discover they're behind only when the time is 90% gone. If a bar on a gantt is 12 weeks long, people will report being on schedule until mid-way through the 10th week, at which time it is virtually impossible to recover.

The lack of knowledge of even a coarse plan effectively prevented engineers in the daily course of their work from knowing if they were on, ahead, or behind the transfer schedule. The managers may have held the information, but it was not available at the working level.

Finally, the engineers did not have access to the resources necessary to effect the transfer. A transfer like this in the midst of a melding of cultures requires lots of face to face interaction as people learn to communicate with and to trust one another. Travel restrictions within Frammis effectively prevented this from happening. Beyond travel, there is an aggravating lack of conference rooms and conference phones with which to communicate to the other site.

When the breakthrough elements are in place, people will consistently work at 80% of what they state as their capacity. If even one is removed, this drops to under 50%. The fact that these three elements were not in place at the working level provides one explanation of why the MR transfer was moving slowly before Stormore purchased the divisions.

Change

Bridges[73] maintains that an organization can only absorb so much change at one time without experiencing a significant drop in productivity and output. The amount of change an organization can absorb is determined by its history -- what the last changes were, when they were, and how they were managed, and by how the new change is being introduced. This is because human beings have to internalize one change before they can successfully deal with another.

The odds of a successful change implementation can be enhanced through management paying attention to the following:

1) Assessing the organization's transitional readiness
2) Making an ending and helping people to let go
3) Bringing people through the period of change
4) Capitalizing on the change as a moment to innovate and experiment
5) Getting people committed to the new beginning

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[73] Bridges, William; "Managing Organizational Transition"; Course Notes; 1989

Comments on each in turn:

1) The organization's transitional readiness
As outlined above, the acquisition of the UMI subsidiary by the Terksville Thin Film Heads Group had not been fully integrated at the time both were purchased by Stormore. Because this transition was not complete, one can argue that Terksville and UMI were not ready for the big change of being acquired by Stormore.

2) Making an ending and helping people let go
The Wall Street Journal announced the sale before it was announced internally. There were four months of rumor and fearfulness before clarity was brought to the benefits package questions high on people's lists of concerns. The ending was not officially announced or very much celebrated.

3) Bringing people through the period of change
An area in which Stormore did well was to hold meetings at every site shortly after the announcement, again at closure, and twice more in the next three months. These meetings served to give employees contact with the new company, to give an avenue to ask questions, and to give a view of the new corporate culture.

4) Capitalizing on the change as a moment to innovate
Stormore stressed that it was a time to re-examine all procedures and sign-off loops with the intent of eliminating valueless steps. This was an appropriate time to do so. Engineer's attentions were distracted from this effort by the reorganization which split engineering into separate TD and manufacturing groups. This will be discussed in more detail below.

5) Getting people committed to the new beginning
Because of the autocratic nature of the reorganization, Stormore hurt their effort toward commitment in the engineering group. One third of the engineering body felt as though they were devalued by the abruptly announced organizational change.

Design and Manufacturing Interaction

Integration between design and manufacturing is a major challenge facing many firms today. Susman[74] has compiled several excellent papers in his 1992 book, Integrating Design and Manufacturing for Competitive Advantage. The following discussion is based on these papers.

The Japanese have succeeded in large part due to cooperation between the various departments within the firm. It is precisely this cooperation that Stormore is beseeching its new employees to exhibit. Stormore wants to "achieve the cooperation between disparate members of the organization and among project teams to focus efforts on goals beyond individual products."[75]

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[74] Susman, Gerald; Integrating Design and Manufacturing for Competitive Advantage, Oxford University Press, 1992.

[75] Sanderson, Susan W.; "Design for Manufacturing in an Environment of Continuous Change"; in Susman, Gerald; Integrating Design and Manufacturing for Competitive Advantage, Oxford University Press, 1992.

To foster such cooperation where little exists is a difficult change to implement. Management must first be cognizant of the problem and then be adamant and resolute in its efforts to improve the situation. Few organizations not under extreme business duress are willing to make the investment necessary to achieve more integration between development and manufacturing.[76]

Most firms are not organized to handle the information flow between development and manufacturing. The databases and organizational structure are not in place to do so. There is not a common language to enable such communication. In general, "coordination of reciprocal interdependence becomes more difficult with increasing differentiation between functions."[77]

Adler[78] suggests the following coordinating mechanisms be used to facilitate TD and manufacturing interaction:

1) Standardization of rules for DFM
2) Plans and schedules
3) Mutual adjustment of Product and Process
4) Teams

Alder then applies these mechanisms to three phases of a project between TD and manufacturing:

1) Develop design and manufacturing capabilities so that there are substantial strengths to build upon
2) Design of product and process
3) Manufacturing and shipping salable product

Several of Alder's categorizations spur comment. In the very first coordinating mechanism; standardization of rules for DFM, there was no agreement between UMI and Terksville on what constituted a process ready for transfer. Plans and schedules, the second mode, were not much in evidence. Mutual adjustment of product and process happened only when something didn't work, and was accompanied by lots of fingerpointing and accusation. Team meetings designed to move the process transfer forward were often poorly attended and the subject of derision. Because UMI and Terksville had evolved independently, methods of transferring information between the sites were not well developed. When the initial process transfers between Terksville and UMI encountered this lack of protocol, the resulting pain came out as interpersonal conflict between the groups. The process transfer suffered. This scenario is not uncommon. Alder states, "When design and manufacturing managers are engaged in turf battles the DFM initiative becomes hostage to the establishment of a power balance". This was the situation Stormore inherited with their purchase.

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[76] Ibid

[77] Susman, Gerald and Dean, James; "Development of a Model for Predicting Design for Manufacturability Effectiveness"; in Susman, Gerald; Integrating Design and Manufacturing for Competitive Advantage, Oxford University Press, 1992.

[78] Alder, Paul, S.; "Managing DFM: Learning to Coordinate Product and Process Design"; in Susman, Gerald; Integrating Design and Manufacturing for Competitive Advantage, Oxford University Press, 1992.

After a seven week quiet period during which nothing seemed to change, Stormore announced the splitting of TD and manufacturing along the geographical boundaries. From one perspective, this made perfect sense. UMI had developed the technology which predicated the purchase. Stormore hopes this technology will serve as the foundation for its products through the next decade. The Terksville site was running at much higher volumes in manufacturing. Further, this separation of TD and manufacturing is the model Stormore has used to advantage in its partnership with its Asian manufacturing partner. Separating TD and manufacturing has worked well for Stormore in the past.

The present may be different. Adding this organizational differentiation to the already strained relationship between TKS and UMI could slow down the rate of organizational learning. Clark, Chew, and Fujimoto[79] state that "the performance of design and development process depends upon the way the development organization executes and integrates numerous design-build-test cycles." They also state that, "Organizational fragmentation makes it difficult to perform steps in parallel." Ideally, they claim that prototypes should be built on the full-scale manufacturing line:

> "Pilot production in the real production line seems to both improve the fidelity of the experiment and to train the members of the local workforce. In this way it serves the purposes of pilot production better than any other approach. The tendency of European firms to locate pilot production in a separate facility appears to lengthen the problem solving cycle and complicate knowledge transfer from pilot to commercial production."

According to Liker and Fleischer[80], three big barriers to the working relationship between TD and manufacturing are:

1) Geographical separation
2) Cultural differences
3) Structural differentiation

The first two of these existed before Stormore purchased the division. One of the first actions taken by Stormore was to add the third.

Recommendations to Stormore

Stormore has four problems to address:

1) Communications between UMI and TKS are hampered by numerous cultural differences, a lack of incentives to work together, and a lack of tools with which to share information. This is a core disability which inhibits ability to get products to market quickly.

2) The MR process transfer from UMI to TKS is hampered by lack of focus and agreement at the lower levels of the organizational hierarchy. Engineers do not posses all the elements necessary to empower their work on the transfer. Progress suffers.

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[79] Clark, K. B., Chew, W. B. and Fujimoto, T.; "Manufacturing for Design: Beyond the Production/R&D Dichotomy"; in Susman, Gerald; Integrating Design and Manufacturing for Competitive Advantage, Oxford University Press, 1992.

[80] Liker, Jeffrey and Fleischer, Mitchell; "Organizational Context Barriers to DFM"; in Susman, Gerald; Integrating Design and Manufacturing for Competitive Advantage, Oxford University Press, 1992.

3) Stormore's purchase of UMI and Terksville has piled a large change on top of an incomplete large change.

4) Stormore's decision to split TD and manufacturing institutionalized another barrier to development and manufacturing interaction. This is apt to further slow product introductions. It also adds to the burden of change.

Stormore must first recognize that the cultures of UMI and TKS have not merged into a single entity and that there is still rivalry and a lack of communication between the sites. Comments in the November 31 presentation indicate that this has been understood by top management. The follow-up on the definition of "We" by the TD manager was excellent. It was timely and a good example of the type of thinking that must become widespread.

In Images of Organization, Morgan[81] states that "routine aspects of everyday practice . . . are incredibly important in understanding how an organization works when no one is really looking. . . . We find that organizations end up being what they think and say, as their ideas and visions realize themselves."

All employees should pause and reconsider whenever they are thinking or saying that the other site is less than adequate. Chances are high that whatever they are hearing to spur their negative response is an inaccurate or incomplete statement. In building relationships -- UMI and TKS are very much still in the building phase -- care must be taken to communicate clearly and to follow up on anything that seems out of place. Employees at both sites are competent individuals striving to make a profitable enterprise. The sites have different strengths and much can be learned from the other.

Management throughout Stormore can meld the UMI and TKS cultures by:

1) Setting a visible example of working closely with their counterparts.
2) Committing to say something good about the other site in public every hour.
3) Never allowing a denigrating statement about the other site to pass without challenge.

This modeling of appropriate behaviors can be augmented with appropriate incentives. These incentives can take many forms. As an example every performance appraisal should be based in part on how well an engineer works with his counterparts at other sites. It is best if the counterparts make a direct input to the appraisal. A second incentive might simply track how often the counterparts meet. A third could be to insist on jointly authored proposals and papers. It is management's responsibility to structure this incentive system. Let people know there will be no advancement without stellar cross-site interaction in the course of ones work.

Hardware to facilitate communication must be put in place. There is no excuse for anyone to ever have to search for a conference phone to hold a cross-site meeting. The two sites should use the same manufacturing database, so process parameters can be easily compared. The same goes for accounting of manufacturing costs. Reliability measures must be common. There must be agreement on what constitutes a process ready for transfer. What level of parallel development, how early manufacturing should be involved in design -- all of this must be discussed and specified.

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[81] Morgan, Gareth; Images of Organization; p133; Sage Publications; CA; 1986.

There are numerous methods available to facilitate these discussions. TQM, QFD, KJs; the list goes on. The discussion pathways must be paved. All sites need to agree on how to work together. It is not enough for management to edict it. Management must model it, and engineers must be held accountable for their interaction with the other locations.

By giving serious attention to the above, Stormore can merge the cultures through improved communication.

At the same time, Stormore should ensure that crisp and clear expectations are given concerning priorities. Communications straight from the decision makers should go immediately to all impacted by every decision. Don't just communicate to the managers. Use the IT network, newsletters and continued presentations to get the message all the way down the hierarchy. Make certain completion dates and the necessity to hit them are well understood. The CEO presentations have started this trend. It should be expanded. Clear expectations are the first leg of empowerment.

The second leg is feedback. Solid planning leads to feedback. Management should ensure that the priorities have detailed plans supporting them.

If the above two legs are in place, management will be deluged with requests for the resources employees require to hit the plan. Management must anticipate this and be ready to provide these resources.

Dealing with the burden of added change is not as straightforward. The communication improvements discussed above will help to realign the groups towards the future. As for the second change of being purchased by Stormore, management should capitalize on the nervous excitement employees feel by building and disseminating a compelling vision. The CEO clearly has a vision and has begun to communicate it in his presentations. Management should realize that with the amount of change the company has undergone, communicating and recommunicating the vision is essential. In Schien's words[82], there is already enough "discomfort and disequilibrium". Stormore is appropriately redefining the discomfort to bear on the working relationships between UMI and Terksville, and on time to market. Now a vision must be put forward to "state how to change and in what direction, thereby providing the path to psychological safety."[83] The refreezing or reinforcement to complete the change process can come by seeking out examples of appropriate behavior to reward, and by making those rewards public.

In light of the research reviewed on design and manufacturing, Stormore should not have split TD and manufacturing engineering. In doing so, they added to the huge burden of change already borne by the company in transition. They added an organizational barrier where none existed, on top of the geographic and cultural barriers to TD::manufacturing communication already in place. By seeking to staff the new TD organization with the "best" engineers, they accentuated and widened the cultural gap between TD and manufacturing.

Given this, Stormore should revert to the previous structure with the engineering groups at each site encompassing both TD and manufacturing engineering. This action would fit with Schien's prescription to embrace errors in the learning process as inevitable and desirable.

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[82] Schien, Edgar; Organizational Culture and Leadership 2nd Edition; Jossey -- Bass Publishers; 1992; p 299.

[83] Ibid

Granted, by reversing an already announced change, Stormore management might seem compromised. They do, however, own the company and the change will be easier to reverse now than later. Some TD engineers might choose to leave. But the ones that would are probably not those attuned to manufacturing. The message Stormore is sending -- work together -- is the correct one.

This organizational change is making it harder to do. The recommendations that follow hold whether or not Stormore recombines TD and manufacturing engineering or leaves them split. The goal of better integration between design and manufacturing is the same in either case.

Co-locate the groups at one site if possible. The UMI group is small compared to the Terksville group. Serious thought should be given to moving the entire organization East. That would eliminate the geographical barrier to communication.

Work to understand the design and manufacturing capabilities of each site. This understanding will provide a basis for future product and process work[84]. Talk to people. Collect data. Chart and publish and discuss Cpks of all operations. Each site will have its strong points. This recommendation dovetails with and reinforces the communication suggestions discussed earlier.

Work to ensure parity between design and manufacturing. Susman[85] found that where unequal status exists, the higher status group will often discount communication from the lower status group. Stormore uses Asian manufacturing contractors where manufacturing engineering is highly valued. Trips to these contractors for manufacturing engineers should be scheduled. This will raise the status of manufacturing -- information gathering trips to the East are often regarded as a perk. Such trips will also reinforce the high expectations Stormore has for manufacturing ability. By holding up its Asian partner as a benchmark, Stormore can incite dissatisfaction and ignite change.[86]

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[84] Alder, Paul, S.; "Managing DFM: Learning to Coordinate Product and Process Design"; in Susman, Gerald; Integrating Design and Manufacturing for Competitive Advantage, Oxford University Press, 1992.

[85] Susman, Gerald and Dean, James; "Development of a Model for Predicting Design for Manufacturability Effectiveness"; p 215; in Susman, Gerald; Integrating Design and Manufacturing for Competitive Advantage, Oxford University Press, 1992.

[86] Spector; "From Bogged Down to Fired Up: Inspiring Organizational Change"; Sloan Management Review; Volume 29; Summer 1989.

To summarize, a culturally exacerbated communication gap accompanied the business units Stormore purchased. Stormore must close this gap before realizing the full benefit of its acquisitions. This can be done by management:

- Modeling the desired behaviors
- Providing incentive for the desired behaviors
- Providing tools -- both soft and hard -- for communication between the sites

- Communicating clear priorities
- Insisting on planning detailed enough to provide engineering feedback
- Providing resources as required

- Communicating a vision
- Rewarding behaviors in line with the vision

- Removing geographic differentiation between the sites
- Removing organizational differentiation between the sites
- Ensuring parity between design and manufacturing

Stormore can establish the "dense reciprocal flows of information" Clark and Fujimoto[87] found are necessary for rapid product development by taking these steps.

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[87] Clark, K. B., Chew, W. B. and Fujimoto, T.; "Manufacturing for Design: Beyond the Production/R&D Dichotomy"; in Susman, Gerald; Integrating Design and Manufacturing for Competitive Advantage, Oxford University Press, 1992.

Appendix A: Raw data from DEV 2^{5-1}

Friction and Breakdown Data from DEV experiment										
Pressure					End Friction				Breakdown Voltage	
	Bias					Increase Friction				
		Power					End Stiction			
			Silicon Thickness					Increase Stiction		
				Carbon Thickness						
High	High	High	Low	Low	1.67	0.28	43	11	414	420
High	High	Low	High	Low	1.50	0.10	56	18	400	294
Low	High	Low	Low	Low	1.78	0.38	42	12	418	404
Low	High	High	High	Low	1.71	0.28	60	32	362	344
Low	High	Low	High	High	1.64	0.23	67	35	320	400
Low	High	High	Low	High	1.80	0.41			470	414
High	High	High	High	High	1.68	0.24			236	350
High	High	Low	Low	High	1.54	0.15	47	19	196	414
Middle	Low	Middle	Middle	Middle	1.56	0.12	43	8	420	263
Middle	Low	Middle	Middle	Middle	1.63	0.26	54	29	380	424
Middle	Low	Middle	Middle	Middle						
Middle	Low	Middle	Middle	Middle						
Low	Low	High	Low	Low	1.78	0.40	64	29	418	502
High	Low	High	High	Low	1.65	0.19	85	30	412	154
High	Low	Low	Low	Low	1.78	0.27	45	13	394	194
Low	Low	Low	High	Low	1.65	0.32			450	382
High	Low	High	Low	High	1.72	0.23	51	21	426	386
Low	Low	High	High	High	1.62	0.17	48	18	422	326
Low	Low	Low	Low	High	1.73	0.22	44	18	420	422
High	Low	Low	High	High	1.48	0.14			428	426
Low	High	High	High	Low	1.79	0.37	52	23	320	316
High	High	High	Low	Low	1.54	0.20	52	23	414	362
Low	High	Low	Low	Low	1.63	0.46	41	11	418	
High	High	Low	High	Low	1.63	0.18	43	11	174	318
High	High	High	High	High	1.60	0.18	53	24	340	340
High	High	Low	Low	High	1.62	0.19	60	34	418	444
Low	High	High	Low	High	1.68	0.25	56	23	496	
Low	High	Low	High	High	1.57	0.30			332	562
Middle	Low	Middle	Middle	Middle	1.54	0.16	47	14	440	346
Middle	Low	Middle	Middle	Middle	1.48	0.18	63	35	414	
Middle	Low	Middle	Middle	Middle						
Middle	Low	Middle	Middle	Middle						
High	Low	High	High	Low	1.62	0.11	52	26	410	416
Low	Low	Low	High	Low	1.56	0.09	44	8	412	
High	Low	Low	Low	Low	1.78	0.34	51	18	240	
Low	Low	High	Low	Low	1.56	0.11	51	20	330	414
Low	Low	Low	Low	High	1.79	0.23	48	15	442	
High	Low	Low	High	High	1.62	0.13	46	11	416	272
High	Low	High	Low	High	1.54	0.21	50	24	420	424
Low	Low	High	High	High	1.59	0.19	50	18	410	

[illegible]