I. INTRODUCTION

In each of the past five years, hard drive capacities have doubled, keeping storage costs low and allowing technophiles and PC users to sock away more data. However, storage buffs believed the rate of growth could continue for only so long, and many asserted that the storage industry was about to hit the physical limit for higher capacities. But according to IBM, a new innovation will push back that limit. The company is first to mass-produce computer hard disk drives using a revolutionary new type of magnetic coating that is eventually expected to quadruple the data density of current hard disk drive products -- a level previously thought to be impossible, but crucial to continue feeding the information-hungry Internet economy. For consumers, increased data density will help hasten the transition in home entertainment from passive analog technologies to interactive digital formats.

The key to IBM's new data storage breakthrough is a three-atom-thick layer of the element ruthenium, a precious metal similar to platinum, sandwiched between two magnetic layers. That only a few atoms could have such a dramatic impact caused some IBM scientists to refer to the ruthenium layer informally as "pixie dust". Known technically as "antiferromagnetically-coupled (AFC) media," the new multilayer coating is expected to permit hard disk drives to store 100 billion bits (gigabits) of data per square inch of disk area by 2003. Current hard drives can store 20 gigabits of data per square inch. IBM began shipping Travelstar hard drives in May 2001 that are capable of storing 25.7 gigabits per square inch. Drives shipped later in the year are expected to be capable of 33% greater density.

In information technology, the term "pixie dust" is often used to refer to a technology that seemingly does the impossible. In the past decade, the data density for magnetic hard disk drives has increased at a phenomenal pace: doubling every 18 months and, since 1997, doubling every year, which is much faster than the vaunted Moore's Law for integrated circuits. It was assumed in the storage industry that the upper limit would soon be reached. The superparamagnetic effect has long been predicted to appear when densities reached 20 to 40 gigabits per square inch - close to the data density of current products.

IBM discovered a means of adding AFC to their standard production methods so that the increased capacity costs little or nothing. The company, which plans to implement the process across their entire line of products, chose not to publicize the technology in advance. Many companies have focused research on the use of AFC in hard drives; a number of vendors, such as Seagate Technology and Fujitsu, are expected to follow IBM's lead.

AFC will be used across all IBM hard drive product lines. Prices of hard drives are unlikely to increase dramatically because AFC increases the density and storage capacity without the addition of expensive disks, where data is stored, or of heads, which read data off the disks. AFC will also allow smaller drives to store more data and use less power, which could lead to smaller and quieter devices.

Developed by IBM Research, this new magnetic media uses multilayer interactions and is expected to permit longitudinal recording to achieve a future data density of 100 gigabits/inch2 without suffering from the projected data loss due to thermal instabilities. This new media will thus delay for several years the impact of superparamagnetism in limiting future areal density increases. It also requires few changes to other aspects of the hard-disk-drive design, and will surely push back in time the industry's consideration of more complex techniques proposed for very high-density magnetic recording, such as, perpendicular recording, patterned media or thermally-assisted writing.

II. CONVENTIONAL MEDIA

BASICS OF MAGNETIC RECORDING

Read-Rite's recording heads are the miniaturized hearts of disk drives and other magnetic storage devices. While they may appear to be simple components, their design and manufacture require leading-edge capabilities in device modeling, materials science, photolithography, vacuum deposition processes, ion beam etching, reliability testing, mechanical design, machining, air bearing design, tribology, and other critical skills. In general, recording heads function according to certain principles of magnetic recording which are based directly on four magnetic phenomena:

Magnetic Phenomena

A.	An electric current produces a magnetic field.
B.	Some materials are easily magnetized when placed in a weak magnetic field. When the field is turned off, the material rapidly demagnetizes. These are called *Soft Magnetic Materials*.
C.	In some magnetically soft materials the electrical resistance changes when the material is magnetized. The resistance goes back to its original value when the magnetizing field is turned off. This is called *Magneto-Resistance* or the MR Effect. Giant Magneto-Resistance, or the GMR Effect, is much larger than the MR Effect and is found in specific thin film materials systems.
D.	Certain other materials are magnetized with difficulty (i.e., they require a strong magnetic field), but once magnetized, they retain their magnetization when the field is turned off. These are

called *Hard Magnetic Materials* or *Permanent Magnets*.

These four phenomena are exploited by Read-Rite in its design and manufacture of magnetic recording heads which read and write data (the source of the company's name) for storage and retrieval in computer disk drive memories, tape drives, and other magnetic storage devices.

Writing Heads

Heads used for writing bits of information onto a spinning magnetic disk depend on phenomena A and B to produce and control strong magnetic fields.

Reading Heads

Reading heads depend on phenomena A, B, and C, and are sensitive to the residual magnetic fields of magnetized storage media (D).

Storage Media (e.g., computer disks)

Magnetic storage media are permanently magnetized in a direction (North or South) determined by the writing field. Storage media exploit phenomenon D.

Writing Magnetic Data

Simplified sketches of a writing head are shown in Figure1. The view from the top of the writing head (left) shows a spiral coil wrapped between two layers of soft magnetic material; on the right is a cross-section of this head as viewed from the side. Note two things in this figure: at the lower end, there is a gap between these layers, and at their upper end these layers are joined together. The top and bottom layers of magnetic material are readily magnetized when an electric current flows in the spiral coil, so these layers become *North* and *South* magnetic poles of a tiny electromagnet. [In a real head, the distance from the gap to the top of the coil is about 30 microns (or 0.0012 inch).]

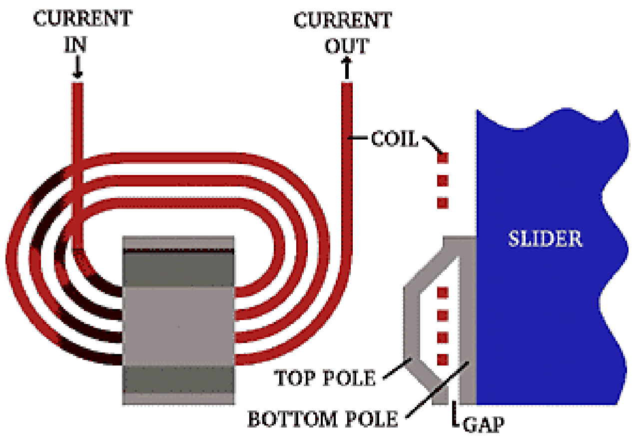


FIGURE 1: A WRITING HEAD

The N-S poles at the gap end of the writing head further concentrate the field to make this region the business end, which is the area where the writing field leaks into space outside the head. When a magnetic storage medium (a spinning computer disk, for example) is put in close proximity with the writing head, the hard magnetic material on the disk surface is permanently magnetized (written) with a polarity that matches the writing field. If the polarity of the electric current is reversed, the magnetic polarity at the gap also reverses.

Computers store data on a rotating disk in the form of binary digits, or bits transmitted to the disk drive in a corresponding time sequence of binary *one* and *zero* digits, or bits. These bits are converted into an electric current waveform that is delivered by wires to the writing head coil. This process is sketched in Figure2. In its simplest form, a *one bit* corresponds to a change in current polarity, while a *zero bit* corresponds to no change in polarity of the writing current. A moving disk is thus magnetized in the positive (North) direction for positive current and is magnetized in the negative (South) direction for negative current flow. In other words, the stored *ones* show up where reversals in magnetic direction occur on the disk and the *zeroes* reside between the *ones*.

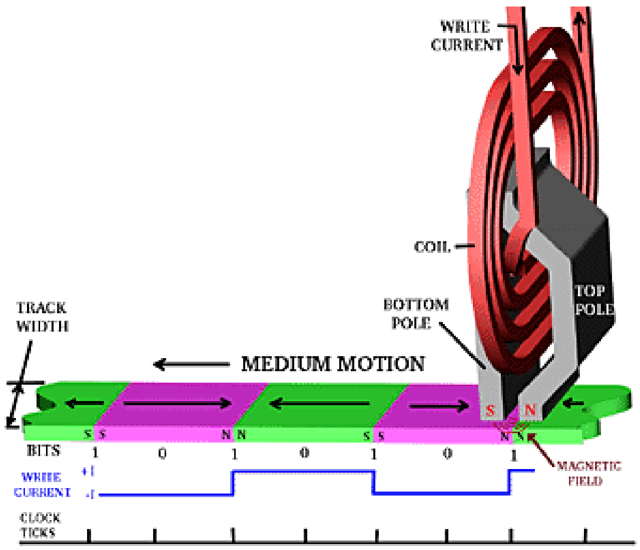


FIGURE 2: WRITING DATA ON A STORAGE MEDIUM

A timing clock is synchronized to the turning of the disk and *bit cells* exist for each tick of the clock; some of these bit cells will represent a *one* (a reversal in magnetic direction such as N going to S or S going to N) and others represent *zeroes* (constant N or constant S polarity). Once written, the bits at the disk surface are permanently magnetized in one direction or the other until new data patterns are written over the old. A fairly strong magnetic field exists directly over the location of *ones* and fades rapidly in strength as the recording head moves away. Moving significantly in any direction away from a *one* causes a dramatic loss of magnetic field strength, thus, to reliably detect data bits, it is extremely important for reading heads to fly very close to the surface of a magnetized disk.

Reading Magnetic Data

In the case of Read-Rite's leading edge products, recording heads read magnetic data with magnetically sensitive resistors called *Spin Valves* which exploit the GMR Effect. These *GMR/Spin Valve* heads are placed in close proximity to a rotating magnetized storage disk, thereby exposing the GMR element to magnetic bit fields previously written on the disk surface. If a GMR head is moved only slightly away from the disk (perhaps 2 to 3 millionths of an inch) the field strength drops below a useful level, and magnetic data cannot be faithfully retrieved.

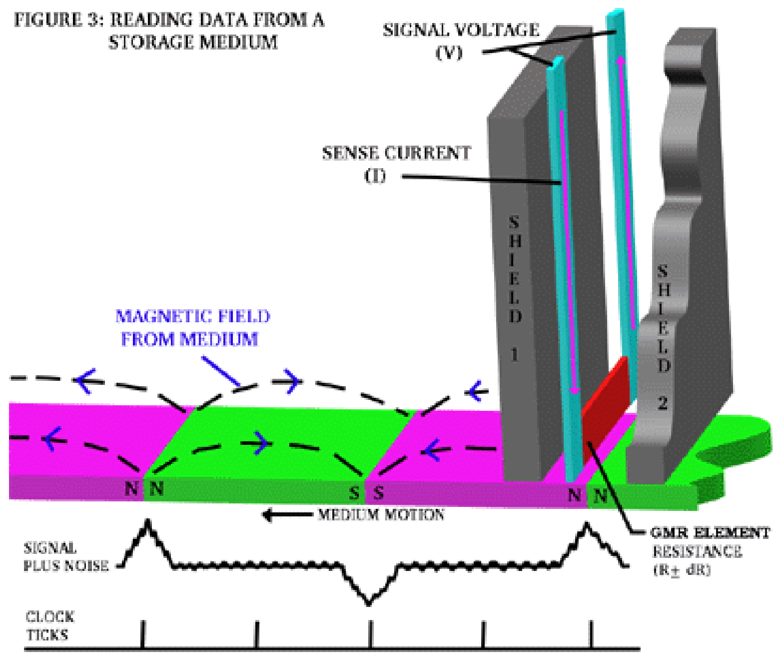


FIGURE 3: READING DATA FROM A STORAGE MEDIUM

When a current is passed through the GMR element, changes in resistance (corresponding to changes of magnetic states arising from written N and S bits) are detected as voltage changes. These voltage fluctuations -- referred to as the *signal*-- are conducted to the GMR sensor terminals. Electrical noise, however, is present in all electrical circuits (GMR heads are no exception) so the combined signal and noise from a GMR reader are sent via wires to the disk-drive electronics for decoding the time sequence of pulses (and spaces between pulses) into binary ones and zeroes. The reading process, including the undesired but ubiquitous noise, is sketched in Figure 3.

Storing more information on a computer disk or other medium is a function of squeezing as many pulses as possible onto a data storage track. However, when pulses are very close to one another, electronic decoders suffer in their ability to separate ones from zeroes in the presence of electrical noise. This problem is alleviated somewhat by placing the GMR element between two layers of soft magnetic material to *shield* the element from the influence of bit fields of adjacent *ones*. These shields, also shown in Figure 3, have the effect of slimming down the data pulses significantly, allowing more information to be stored and faithfully retrieved.

III. SUPERPARAMAGNETIC EFFECT

Computers get better and better, faster and faster; and, of all computer components, probably the greatest rate of evolution belongs to the stalwart hard drive. On a daily basis, the storage capacity and speed of hard drives increases, while their cost just keeps on shrinking. This is one of those rare situations in which both consumers and companies profit; but something called superparamagnetic effect may soon bring an end to this golden age.

As hard drives become capable of storing more information and accessing it at faster speeds, their data becomes more susceptible to corruption. This data-density barrier is known as the superparamagnetic effect (or SPE). Before going on to say more about SPE, though, it might be helpful (and scenic) to take a brief detour to examine the technology at the hub of your average hard drive.

Today's hard drive resembles a small record player that's capable of stacking its disks, or platters, to hold up to eight of them at a time. Each platter is covered with a magnetic film that is ingrained with tiny particles called bits. When a read-write head (looking like the needle of a record player) passes over the bits, it either magnetically aligns the particles to record information (turning them into series of 1's and 0's), or it reads them in order to access previously-stored data. These operations take place at phenomenal speeds; the platters spin around thousands of times per minute, and both sides of them are scanned simultaneously by read-write heads.

Advances in hard drive technology continue to increase the number of bits that fit onto each platter. Bits are getting smaller and smaller, making for greater storage capacity, but also bring the SPE barrier closer and closer. So what exactly does SPE do? Basically, SPE destabilizes the 0 or 1-orientation of magnetic bits, resulting in corruption of stored data. When the energy in the bits' atoms approaches the thermal energy around them, the bits start randomly switching between 0's and 1's. In layman's terms, SPE makes bits flip out.

The superparamagnetic effect originates from the shrinking volume of magnetic grains that compose the hard-disk media, in which data bits are stored as alternating magnetic orientations. To increase data-storage densities while maintaining acceptable performance, designers have shrunk the media's grain diameters and decreased the thickness of the media. For media limited noise signal/noise ratio is proportional to square root of N, where N is the number of media grains per bit.

$$\text{Signal/Noise} \sim N^{0.5}$$

At samller grain volumes, grains can randomly reverse thair magnetisation direction, resulting in an exponential decay whose rate strongly depends on temperature. The resulting smaller grain volume makes them increasingly susceptible to thermal fluctuations, which decreases the signal sensed by the drive's read/write head. If the signal reduction is great enough, data could be lost in time to this superparamagnetic effect.

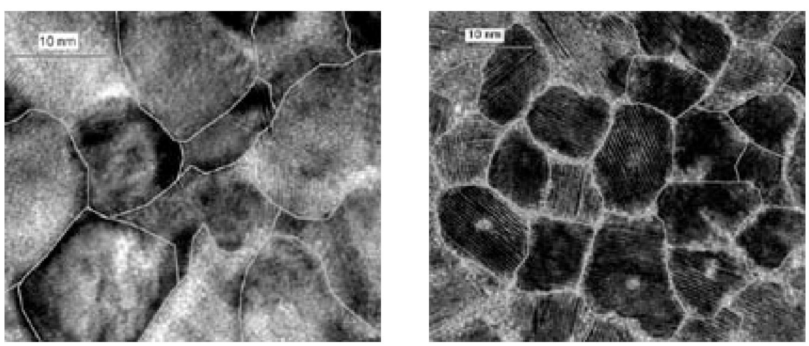


Fig. 4. TEM of the grain structures in magnetic media. (magnification = 1 million)

In Figure 4 are transmission electron micrographs (TEM) for two different disk media illustrating how the grain structure has changed over time. The TEM on the left is a magnetic media that supports a data density of about 10 gigabits/inch2 with an average grain diameter of about 13 nanometers. The magnetic media on the right supports a data density of 25 gigabit/inch2 with an average grain diameter of about 8.5 nanometers.

Historically, disk drive designers have had only two ways to maintain thermal stability as the media's grain volume decreases with increasing areal density:

1) Improve the signal processing and error-correction codes (ECC) so fewer grains are needed per data bit.

2) Develop new magnetic materials that resist more strongly any change to their magnetization, known technically as higher coercivity.

But higher coercivity alloys also are more difficult to write on. While improvements in coding and ECC are ongoing, IBM's new AFC media is a major advancement because it allows disk-drive designers to have their cake and eat it too: It is easy to write at very high areal densities but is much more stable than conventional media.

IV. AFC MEDIA

Antiferromagnetically Coupled (AFC) media (synthetic ferrimagnetic media (SFM) or Laminated Antiferromagnetically Coupled (LAC) media) technology is expected to extend the lifetime of longitudinal magnetic recording technology. LAC media differ from the conventional media by their structure and functionality. Conventional recording media have one or more magnetic layers, which may be coupled ferromagnetically to each other. In AFC media, there are at least two magnetic layers, but the magnetic layers are coupled antiferromagnetically. In comparison to conventional media, AFC media exhibit similar or better recording performance. But, at the same time, AFC media show much improved thermal stability, which makes them attractive.

The principle of AFC media is based on adding extra energy in the form of antiferromagnetic coupling to stabilize the bits. Conventional disk media stores data in only one magnetic layer, typically of a complex magnetic alloy (such as coblat-platinum-chromium-boron, CoPtCrB). AFC media is a multi-layer structure in which two magnetic layers are separated by an extraordinarily thin -- just three atoms thick -- layer of the nonmagnetic metal, ruthenium. This precise thickness of the ruthenium causes the magnetization in each of the magnetic layers to be coupled in opposite directions -- anti-parallel -- which constitutes antiferromagnetic coupling. A schematic representation of this structure is shown in Figure5.

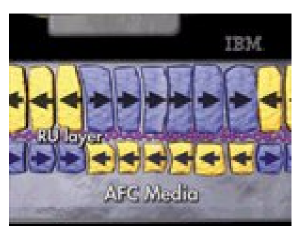


Fig. 5. Schematic representation of AFC media with single magnetic transition.

The storage medium used has a layered architecture. This is shown in Figure 6. These layers are magneto-statically and anti-ferromagnetically coupled to each other. All magnetic parameters for each layer can be set differently. One layer can be used as the soft underlayer for a perpendicular medium or this two layer system can be used to model antiferromagnetically coupled media.

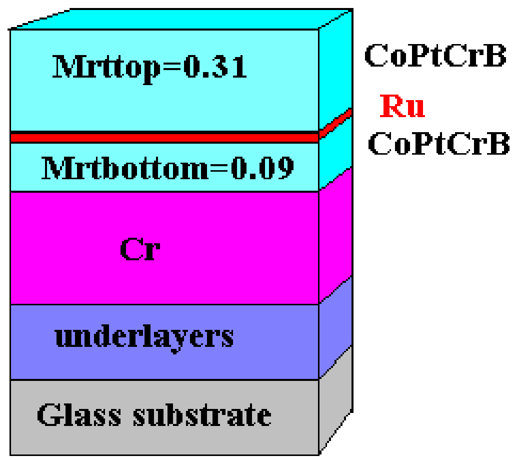


Fig. 6. Coupled Layers Of Storage Media

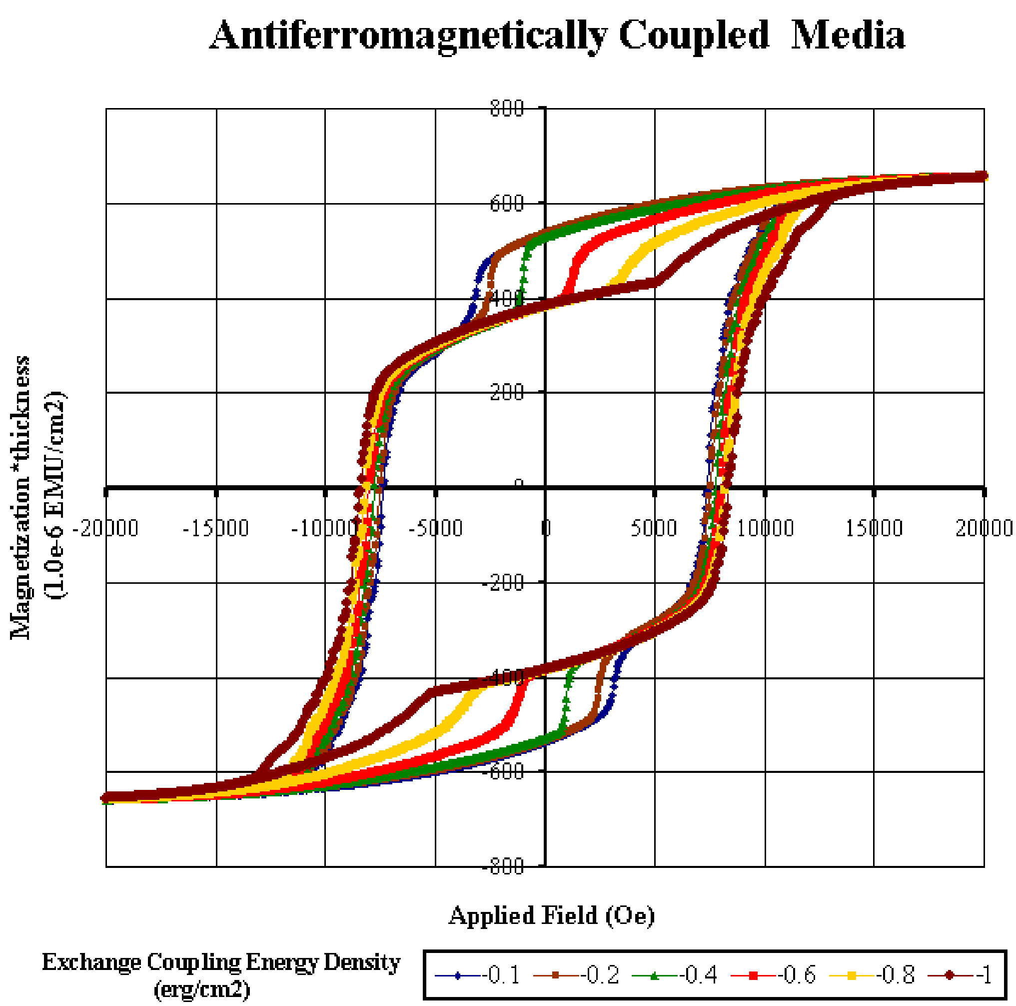
When reading data as it flies over the rapidly rotating disk, a disk drive's recording head senses the magnetic transitions in the magnetic media that coats the disk. The amplitude of this signal is proportional to the media's "magnetic thickness" -- product of the media's remanent magnetic moment density ("M_r") and its physical thickness ("t"). As data densities increase, the media's magnetic thickness (known technically as M_rt) must be decreased proportionately so the closely packed transitions will be sharp enough to be read clearly. For conventional media, this means a decrease in the physical thickness of the media.

The key to AFC media is the anti-parallel alignment of the two magnetic layers across each magnetic transition between two bits. As it flies over a transition, the recording head senses an effective M_rt of the composite structure ($M_r$teff) that is the difference in Mrt values for each of the two magnetic layers:

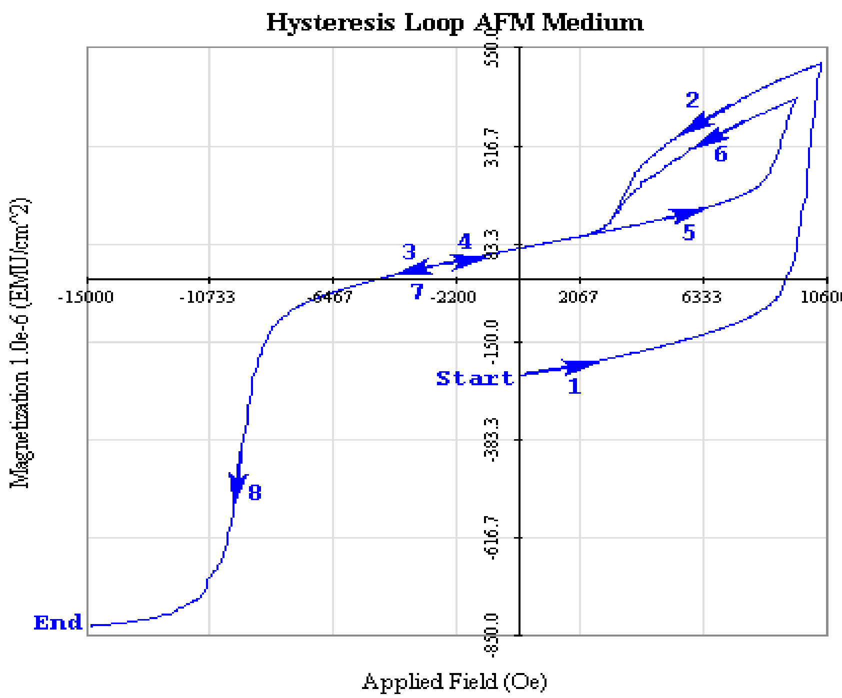
$$M_r teff = M_r ttop - M_r tbottom$$

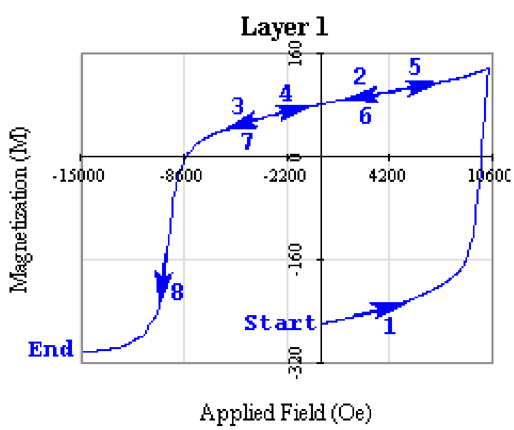
This property of the AFC media permits its overall M_rt to be reduced -- and its data density increased -- independently of its overall physical thickness. Thus for a given areal density, the M_rt of the top magnetic layer of AFC media can be relatively large compared with single-layer media, permitting inherently more thermally stable larger grain volumes.

Below the hysteresis loop from such an AFC system is shown. For the hysteresis loop below the interlayer exchange energy density was from 0.1 to 1.0 erg/cm2.



As a demonstration of the complex interactions that are involved with antiferromagnetically coupled layers, shown below is a simulation in which minor loops are traced out by varying the applied field. In the three pictures the numbers show the approximate progression of the magnetization as a function of the sweep field. The first graph is the net magnetization in the dual layer AFC medium. The two smaller graphs below it show the magnetization in each layer.





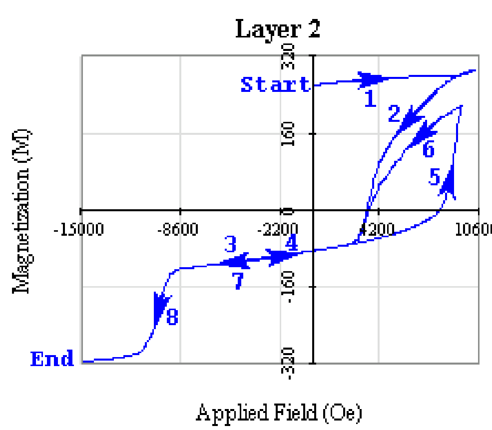


Figure 7 compares projections made based on measurements of the expected signal amplitude loss after 10 years in conventional single-layer media with that in AFC media. As the Mrt of the conventional media decreases with reduced film thickness and grain diameter, thermal effects rapidly shrink its magnetic amplitude. This dramatic signal loss is at the heart of the superparamagnetic effect. Acceptable levels of signal decay vary depending on system design but typically range between 10-20%.

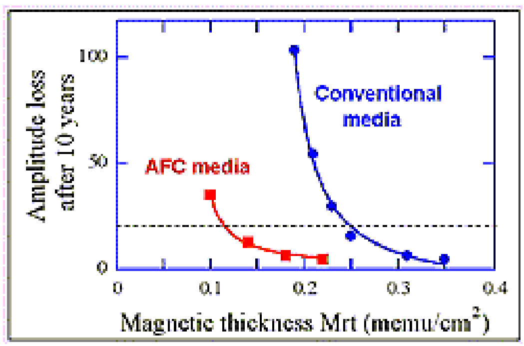


Fig. 7. Amplitude loss of AFC and conventional media

Theoretical Model

The media is simulated with grains of two-layer hexagonal array having 3-D spins as shown in Fig. 8. Grains grow in an epitaxy form, therefore the in-plane grain size of the FM1 layer and FM2 layer are assumed to be the same and is represented with a stack up structure. Easy axis of FM1 and FM2 for a stack up grain is assumed in same direction. All the grains in the system are assumed same size. The easy axes are 2-D randomly distributed.

The normalized effective field for each moment is the total field of **hk** anisotropy field, **hexh** exchange field, **hZeeman** Zeeman field, **hmag** magnetostatic field and **hJ** antiferromagnetic coupling field (in the normalized form).

$$\mathbf{heff = hk + hexh + hZeeman + hmag + hJ}$$

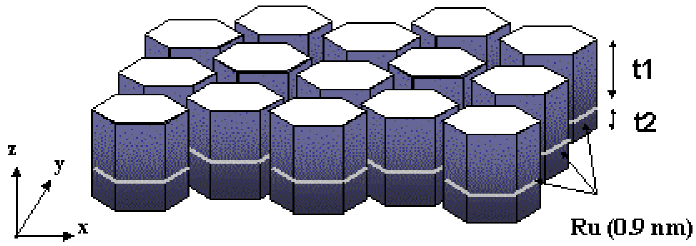


Fig. 8 .Geometry structure representing the grains in the films. Epitaxial growth is assumed for FM1 on FM2.

Research work on AFC media in IBM

Magnetic Properties and Reversal Mechanism

- Hysteresis Loops Simulation
- Switching Field Control
- Systematic Parametric Study
- Effect of Antiferromagnetic Coupling Constant, J
- Effect of Anisotropy Constant, K
- Effect of Thickness Ratio
- Interlayer Exchange Coupling Effect
- Magnetostatic Interaction Effect

Recording Performance

- Recording Patterns
- Transition Noise
- Cross Track Profile

Thermal Stability Study

- Energy Barrier Analysis
- Magnetization Decay
- Superparamagnetic Effect

V. THERMAL STABILITY

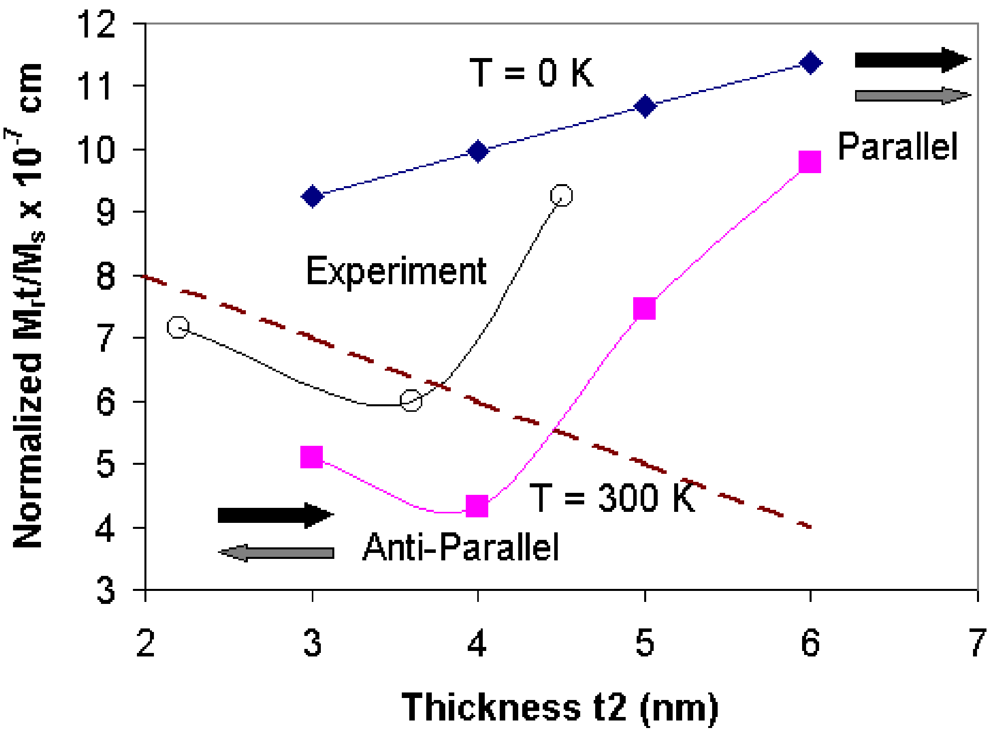
Issue of Thermal Stability The growth rate in the areal density of hard disk drives has been around 60-100% per year, in the last decade. Such a tremendous improvement was made possible, because of the introduction of GMR heads, reduction in grain size and thickness of media and so on. As far as the media is concerned, a reduction in grain size and thickness cannot continue forever, because the anisotropy energy (KuV), which maintains the stability of the bits, gets reduced. For small values of KuV, the thermal energy (kBT) at room temperature increases the probability of data erasure. This thermal instability is one of the major obstacles towards achieving areal densities beyond 40Gb/in2.

Ways to Overcome Thermal Instability

The thermal stability of the media can be improved by choosing media materials with a higher Ku. Materials with a Ku that is 10 times higher than that of current media materials already exist. But, larger Ku materials require larger writing fields. There is no head material that can produce writing fields larger than about 25T. Therefore, it is sometimes, said that thermal instability is an issue coming from the head materials, not from the media materials. The writing field can be reduced, if we choose materials with a high Ku and high Ms. In media materials, grain-boundary segregation of a non-magnetic material such as Cr is always needed for obtaining low noise. But, when Cr is added to the media material, the Ms also decreases. Therefore, it is very difficult to have a high Ms and a low noise media. An innovative way to overcome thermal instability is to provide some additional energy to KuV, without increasing the remnant magnetization. This condition is satisfied if we use an antiferromagnetic underlayer or some kind of antiferromagnetic coupling in the magnetic layers.

A low Mrt is desired in media materials to achieve low noise. One of the major advantages of AFC media is that a low M_rt (necessary for a low noise) can be achieved without sacrificing the thermal stability. Experts initial investigations were on the fundamental understanding of how M_rt reduction could be achieved. Theoretical model and experiments indicated that the Mrt reduction depends on a few experimental parameters such as the anisotropy constant, magnetization and thickness of the bottom layer. In addition, our experiments and simulation studies indicated that thermal energy (which is available at ambient temperature) also plays a major role in the M_rt reduction. It was found that the thermal energy helps to achieve M_rt reduction, even for small values of antiferromagnetic coupling constant, J (as low as 0.1 erg/cm2), observed in AFC media.

Now, it is well known that the AFC media offer better thermal stability in comparison to the conventional media. The source for the improved thermal stability is the antiferromagnetic coupling strength (measured as J). So by this antiferromagnetic coupling strength the energy barrier for magnetization reversal has increased. This leads to a larger thermal stability than using a single ferromagnetic layer. Therefore, increasing J further (from 0.1 erg/cm2, the current value of J, as reported by all other researchers) is a way to increase the thermal stability of the AFC media. Media group of DSI has recently developed a technology, which can give rise to an effective J of about 0.8 erg/cm2 in LAC media with a low M_rt and high thermal stability.



Thermal Energy Inclusion in Micromagnetic Simulation

(Etotal = EAnis + EZeeman + EExchange + EMagnetostatic + EAnti + EThermal)

VI. ADVANTAGES

- AFC media is the first dramatic change in disk drive design made to avoid the high-density data decay due to the superparamagnetic effect. The 100-gigabit density milestone was once thought to be unattainable due to the superparamagnetic effect. A natural solution to this problem is to develop new magnetic alloys that resist more strongly any change in magnetic orientation. But recording data on such materials becomes increasingly difficult. AFC media solves this problem.

- Another important advantage is its thermal stability. As the M_rt of the conventional media decreases with reduced film thickness and grain diameter, thermal effects rapidly shrink its magnetic amplitude. This dramatic signal loss is at the heart of the superparamagnetic effect. Acceptable levels of signal decay vary depending on system design but typically range between 10-20%. In comparison, AFC media has the thermal stability of conventional media having about twice its magnetic thickness. In the future, AFC media structures are expected to enable thermally stable data storage at densities of 100 gigabits per square inch and possibly beyond.

- Another advantage is the noise reduction in AFC Media. In AFC media, the magnetization of top and bottom layers should be aligned in opposite directions, at remanence, if a low noise is to be achieved. This antiparallel alignment of moments is decided by the competing energies. The research work in DSI revealed that, a low M_rt (in other words, a low noise) can be achieved by, decreasing the anisotropy constant or magnetization of the bottom layer decreasing the thickness of the bottom layer or, decreasing the anisotropy constant-thickness product increasing the interface coupling constant, J .

- Two additional advantages of AFC media are that it can be made using existing production equipment at little or no additional cost, and that its writing and readback characteristics are similar to conventional longitudinal media. The output pulse sensed by the recording head is a superposition of the fields from transitions in both the top and bottom magnetic layers. As with conventional media, this output is detected as a single pulse, so no changes to the disk drive's recording head or electronic data channel components are required.

- This multilayer coating (antiferromagnetically coupled media), and it's expected to enable hard disk drives to store 100 billion bits of data per square inch of disk area by middle of 2003.
  - Desktop drives -- 400 gigabytes (GB) or the information in 400,000 books;
  - Notebook drives -- 200 GB, equivalent to 42 DVDs or more than 300 CDs;
  - IBM's one-inch Microdrive -- 6 GB or 13 hours of MPEG-4 compressed digital video (about eight complete movies) for handheld devices.

VII. CONCLUSION

Because of advances in disk technology, like IBM's pixie dust, we can expect to see 400GB desktop drives and 200GB notebook drives within another year or so, according to IBM scientists. Fujitsu is using similar technology. Fujitsu's SF Media uses a recording medium made up of two magnetic layers separated by a thin layer of ruthenium.

In summary, IBM has developed and is now mass-producing a promising new disk-drive media technology based on antiferromagnetically coupled multilayers that can enable significant areal density increases while maintaining the thermal stability of recorded data. This advancement will permit magnetic hard-disk drive technology to extend far beyond the previously predicted "limits" imposed by the superparamagnetic effect.

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ABSTRACT

Pixie dust is the informal name that IBM is using for its antiferromagnetically-coupled (AFC) media technology, which can increase the data capacity of hard drives to up to four times the density possible with current drives. AFC overcomes limits of current hard drives caused by a phenomenon called the superparamagnet effect (basically, alterations in magnetic orientation). The "pixie dust" used is a 3-atom thick magnetic coating composed of the element ruthenium sandwiched between two magnetic layers. The technology is expected to yield 400 GB (gigabyte) hard drives for desktop computers, and 200 GB hard drives for laptops by the middle of 2003.

CONTENTS

ACKNOWLEDGEMENT

I thank God Almighty for the successful completion of my seminar. Sincere feelings of gratitude for Dr.Agnisharman Namboothiri, Head of the Department, Information Technology . I express my heartfelt gratitude to Staff-in-charge, Miss. Sangeetha Jose and Mr. Biju, for their valuable advice and guidance. I would also like to express my gratitude to all other members of the faculty of Information Technology department for their cooperation.

I would like to thank my dear friends, for their kind-hearted cooperation and encouragement.