PRESENT STATUS AND FUTURE MAGNETIC DATA STORAGE

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Abstract

Today's typical hard disk drive for PC applications provides storage of several hundred mega-bytes in a small 2.5 or 3.5 inch format. This is quite impressive when compared to the 5 to 10 mega-bytes in a full height 5.25 inch PC drive of 1984. To continue to achieve these disk drive improvements the areal storage densities will have to grow from the approximate 0.5 Giga-bits per square inch of today, to and beyond, 10 Giga-bits per square inch during the next few years. Scaling projections indicate that sub-micron track widthsπ and sub-100 nm bit lengths will be required. This places extreme demands on both the physical and magnetic properties of the recording medium.

After many years of promising research the magneto-optic disk drive is now a commercial reality. The removeability of the media has represented the greatest technical and commercial advantage over hard disk drives. However, both the magneto-optic drive and media are far more complex than today's hard disk drive and so the hard disk has enjoyed a more prominent position in the market place. Nevertheless, as futuristic recording concepts are explored it is becoming increasingly obvious that optical concepts and new magnetic recording concepts are merging.

Here we describe some of the future media challenges and approaches to solving both the near term, long term and futuristic data storage technological problems.

I. Introduction

The recent technological advances of the personnel computer as well as the computationally intensive work station has provided an insatiable demand for rotating disk storage. The increasingly large program and data files, for applications such as image processing, has finally driven the need for optical storage devices. At the same time the low cost and short access times of the hard disk drive have kept this technology on a growth curve that is even steeper than for the semiconductor industry. For each of these technologies the performance figure of merit is the areal recording density. Assuming the recording medium can reliably support the data bit cell size the limiting factor in advancing the areal density is the combined resolution of the record/playback transducer as it interacts with the storage medium. In the case of optical storage this recording density is largely determined by the diffraction limit of the optical system. Removability of the optical storage medium has lead to standardization of the recording formats and hence standardization of the areal density. For the enclosed hard disk system, the storage format is transparent to the user and so many possibilities abound. Ultimately the recording resolution is largely determined by how close the record/playback head can be placed to the magnetic medium. The introduction of sputtered thin film media onto electrolessly plated NiP on an alloy (Al-4 % Mg)

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substrate has led to a substantially smoother surface enabling record and playback heads to become closer to the medium. These advances have recently lead to an approximate 60% compound annual growth rate for areal densities [1] plus several demonstrations of areal densities in the Gb/in^2 range [2-4]. The emerging commercially available technology today incorporates over 1 Gb/in^2 areal densities and remain on a 60% per year growth curve.

The question of what the ultimate limits of the areal density for both the optical and hard disk drive naturally arises and people are starting to creatively think about new ways to push beyond the conventional storage approaches. Nevertheless, it is valuable to address how far traditional recording processes, as we know them today, can be taken. In 1992, Murdock et al. [5] described several possible hard disk recording formats and outlined the required mechanical, magnetic, and recording performance requirements to achieve 10 Gb/in^2 areal densities. The selection and matching of the head and media components as well as the tracking and signal processing techniques is currently a complex iteration process and evaluation of each of these individual components is somewhat hampered by the lack of the other. Here we will discuss some of the issues involved in developing hard disk media while following on the traditional recording path and develop a philosophy for developing media when advanced recording and playback heads are not available. By example, we will try to put into perspective where media technology is today and what limits its performance. For discussion purposes, we could assume that the limit to this traditional approach might lie somewhere in the range of 10 to 50 Gb/in^2 and then discuss approaches to go beyond this regime. While the storage materials for magneto-optic disk and the magnetic hard disk drive are considerably different the fundamental understanding of the magnetic properties and ultimate storage limits is the same. In fact for very futuristic recording densities of greater than 100 Gb/in^2 we anticipate that the two technologies may merge. Hence, we initially focus on methods to manipulate and evaluate hard disk materials and then move on to consider more futuristic systems.

II. Media Requirements of Magnetic Disk Storage

In magnetic recording the stored data state is contained in the reversal of the magnetic state of the medium. This magnetic flux transition is sense by the finite gap length of the playback head and as such the ultimate resolution limit is determined not only by what the medium will support, but by the head gap length and the proximity of the gap to the medium surface. This playback signal falls off rapidly as the head to medium spacing, d, increases for any given recorded wavelength, λ. The signal loss is characterized as

$$e = -54.6d/\lambda \text{ (dB)} \tag{1}$$

Hence a compromise is made in recording systems between the ability to stay on a data track and the linear recording density. For several years disk drive designers have maintained a fairly constant recording trackwidth to linear bit density ratio. Scaling the current areal density to a 10 Gb/in^2 system yields a format that would call for 25,400 tracks per inch (tpi) (0.5 micron read head width) and linear density of 400,000 bits per inch (bpi). The data is typically encoded such that one flux transition can represent more than one data bit. Hence a modern 4/3's rate code would then dictate a 300,000 flux changes per inch (fci) linear density.

Soft high moment FeN$_x$ materials are currently being investigated as recording heads and so it is reasonable to assumed that these high moment inductive heads will be available for recording. At the same time we assume that high sensitivity spin-valve head [6] technology will be available for playback. The playback head dynamic range and head-medium spacing, then determines the desired moment of the medium. Scaling arguments [5] indicate that for a 30-40 nm head to the center of medium spacing, a $M_r\delta$ = 0.4 to 0.6 memu/sq.-cm. is needed to optimize head response while preventing head saturation non-linearities during playback. Here $M_r\delta$ is the product of the remnant magnetization and the magnetic medium thickness. The magnetic medium is composed of a random set of different in-plane orientations and sized grains or magnetic switching units and it normally takes several of these to form the flux reversal. The variation in the location of the flux reversal from the ideal represents medium noise in the signal. From this medium noise view point, it turns out to be especially advantageous to lower the recording head to medium spacing as this improves the sharpness of the transducer's magnetic field gradient and sharpens the recorded transition and it location. Fortunately, the low $M_r\delta$ that spin-valve head technology requires also minimizes the transition demagnetization effects to allow higher linear bit densities. As a rule of thumb the flux reversal spacing is limited to approximately πa_x [7] where a_x is the transition length parameter. Hence, to achieve 300Kfci a_x should be less than 27 nm. The coercivity of the medium should then approach 3000 Oe while δ should be less than 15 nm.

While there are many sources of noise imposed upon the signal, it is anticipated [6] that the medium noise will slightly dominate electronics noise and the head noise and so an isolated signal pulse to broad band media noise ratio of 27-30 dB is required for 10 Gb/in^2 [5]. Fortunately, we have the experience of particulate recording media as a guide in understanding the media noise issues. Baugh et al. and Belk et al. [8,9] showed that media noise, measured in the frequency domain, is the smallest when the magnetic medium is composed of small, well isolated, magnetic particles. For particulate media they found that the noise power was nearly a constant, as a function of transition density, and the smallest at high recording densities. In thin metal films it is common for the individual magnetic grains to touch, interact via magnetic exchange coupling and not to switch independently. Hence, they found that for thin film media, the noise power increases linearly with increasing transition density as much of the noise is associated with the transition when the medium is exchange coupled. They also found that as the transitions begin to approach each other and interact the noise power increases supra-linearly. Hence, it has become the objective of hard disk medium designers to find magnetic material systems and deposition processes which result in magnetic grains (magnetic switching units) which do not touch and minimize these interactions. However, even if the medium is successfully made without exchange coupling there are still magnetostatic interactions and the number of randomly oriented switching units sampled by the head is finite so there is still medium noise which ultimately limits the recording signal-to-noise ratio and hence the recording density.

When a particulate-like medium is dc-erased, the particles are magnetized, largely, all in one direction and fluctuations in the magnetization sensed by the head are due to either non-uniformities in the density of particles or in the random orientation of their magnetic axes. These statistically independent fluctuations yield a Gaussian probability distribution. This gives a noise power proportional to the number of particles sampled, while the signal power is proportional to the square of the number. Hence, the lowest particulate medium noise results when the particles are small so that the number of particles sensed by the head field is maximized and when the size and orientation distribution of the particles is uniform. For the Baugh type of analysis, the lowest noise is observed when the medium is in the ac-erased state as the magnetization of individual particles orient to a flux closure condition which minimizes the external fields that the head senses. The power signal-to-noise ratio (SNR_P) is approximately given by

$$SNR_P = \frac{W\lambda/2}{d^2\pi/4} \tag{2}$$

where W is the trackwidth, d is the grain diameter and λ is the recorded wavelength. For the 10 Gbit/in^2 example to achieve a 30 dB SNR_P with W = 0.5 micron and λ = 170 nm then d should be 7.35 nm. At grain sizes this small there is some concern that the recorded transitions may not be thermodynamically stable. However, if the recording system could perform at a higher error rate or if better error correction signal processing is developed a 20 dB SNR_P might be tolerated and then d could be increased to 23.2 nm.

Thin film media are commonly composed of closely packed, randomly oriented in-the-plane grains which are either magnetically exchanged coupled at the grain boundary, grouped as exchanged coupled clusters of grains, or, at best, grains which are somewhat isolated by non-magnetic material. The later behaves as particulate media, while the former behaves as large regions of continuous magnetization. For the former, the dc-erased state is the lowest noise situation as the media can be viewed as one large domain with no flux leakage from the media surface. However, at a flux reversal, the fluctuation amplitude manifests itself as large medium noise. Practically, for a medium noise limited system, the flux spacing, πa_x is usually set to be at or slightly beyond the onset of this supra-linear regime. Therefore the following three simultaneous conditions are desired in order to achieve the best Baugh [8,9] type of medium noise plot: 1) Small isolated magnetic units to give a low slope in the linear regime. 2) Small, uniform, uncoupled, aligned grains to give a low dc noise. 3) A recording transition density chosen to occur prior to the onset of the supra-linear regime. If all three of these conditions are fulfilled then the transition fluctuation amplitude is largely determined by the dispersion in the media characteristics (uniformity of grain size, orientation, exchange coupling, stress, etc.). These fluctuations can only be exacerbated by the a poor record head field gradient. That is, if the head field gradient is poor, then both a_x [7] and the fluctuation (noise) of the transition location will be large [10,11]. Hence it is extremely important to minimize the head to medium spacing not only to increase signal and to maximize resolution, but also to reduce medium record noise.

Table 1 describes and Figure 1 compares medium noise for several state-of-the-art media as well as advanced media being developed toward the 10 Gb/in^2 objective. These data were obtained using a 5 micron wide Read Rite Tripad head with a 0.22 micron gap and flying at approximately 25 nm (at 7.1 m/sec. velocity). Focusing on the commercially available CoCrTa (0.4 to 0.5 Gb/in^2) and the CoCrPt (1.0 Gb/in^2) medium we observe examples of the medium noise characteristics discussed above including the supra-linear increase in noise.

Media	Magnetic Properties		Substrate			
Material	Hc (Oe)	Mrt (memu/cm^2)	Material	Surface Finish	Roughness Rrms (nm)	Overlayer Thickness (nm)
CoCrTa/Cr	1900	2.1	NiP/Al	Textured	8.7	15 (C)
CoCrPt	2280	1.0	NiP/Al	Textured	5.0	15 (C) 7 (Cr)
SmCo/Cr	3000	0.6	Glass	Smooth	1.3	10 (C)
CoCrPt/Cr	3000	0.55	NiP/Al	Super Smooth	0.4	5 (C)
CoCrPt/ Cr/NiAl	2760	0.53	NiP/Al	Super Smooth	0.4	5 (C)

Table 1. Physical properties of magnetic disk

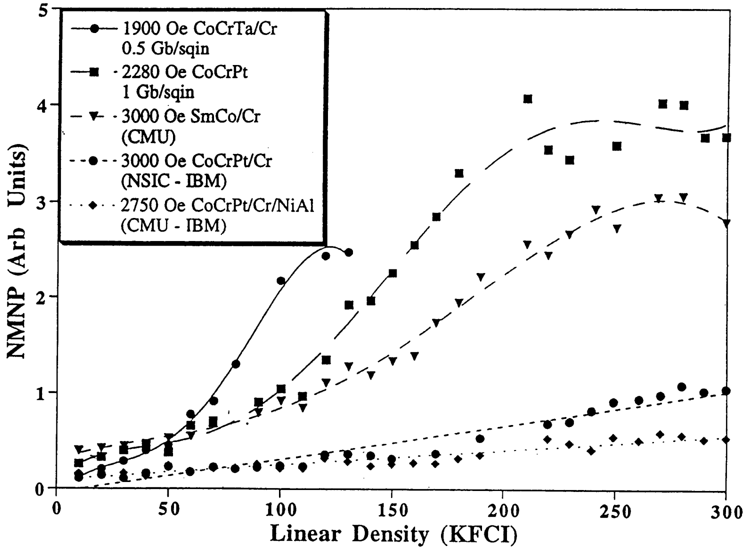

Figure 1. Medium noise power vs. linear recording density

As the grain size is reduced to decrease noise and as the thermal energy fluctuations threaten the stability of the recorded bit it is important to maximize the crystalline anisotropy. The product of the anisotropy energy and the volume of the magnetic switching unit represents the barrier to magnetization reversal in the presence of thermal fluctuations. Charap and Lu's [12] modeling indicated that for 400 Kfci recording and pure cobalt parameters ($K_u = 4.5x10^6$ erg/cc, $M_s = 1400$ emu/cc), a grain size below 8 nm would tend to be thermally unstable in the presence of the demagnetizing field of the recorded flux transition. A 10 Gb/in^2 medium should then have magnetic units in the 10-12 nm diameter range. One philosophy to achieving high coercivity (high effective anisotropy energy) is to build grains of such crystalline perfection that the magneto-crystalline anisotropy is maximized and not compromised by lattice strain, defects, or grain boundary anomalies. Also, alignment of the anisotropy axis of the grains along one direction (preferably the record track direction) would help to maximize the coercivity. (A three dimensional ensemble of non-interacting Stoner-Wohlfarth particles effectively decreases the anisotropy field and the potential coercivity of the media by about 50%.) The question then arises: What can be done during the construction of the media to maximize the anisotropy energy barrier as the volume of the magnetic particle is reduced to improve medium noise.

III. Media Construction

There are several potential approaches to increase the anisotropy energy while decreasing grain size and noise. Daval and Randet [13] showed that an underlayer of textured Cr could significantly improve the magnetic properties of a Co alloy thin film by orienting the HCP c-axis into the film plane via inducing epitaxial growth in the Co alloy. Much work has been published on how the Cr underlayer influences the Co alloy microstructure and magnetic properties. The medium's coercivity and noise performance is largely determined by the Co alloy composition, grain size, and crystal orientation, perfection, and isolation. The underlayer largely effects the latter four of these via promoting epitaxial growth onto the Cr crystallites. Likewise, the substrate surface strongly influences the Cr growth via both surface bonding energy [14] and roughness. Figure 2 shows this traditional structure of thin film media. The lubricant and carbon overcoat on the magnetic layer provides both corrosion protection from the atmosphere and mechanical protection from the head slider when it touches during operation or when the drive is powered down and the head slider lands on the disk surface. At the same time these represent additional head to medium spacing and so their thicknesses must be minimized.

Depending upon the growth conditions [14-16] the BCC Cr tends to develop with a variety of crystallographic textures. The closest packed planes are {110} and so at low substrate temperatures, or when prepared with a substrate bias, the low energy state (110) texture is obtained which promotes an epitaxial (10.1) cobalt texture. Since the atomic sizes of Cr and Co are similar, the atomic spacing of the atoms at these two surfaces approximately match and so, on a small grain-size scale, an epitaxial growth results. This places the magnetic easy axis (c-axis) of the HCP Co tilted approximately 28 degrees from the film plane. Since the textured Cr has axes in-plane, the in-plane magnetization components of the Co crystallites are random in-plane. On the other hand, under higher temperature deposition conditions, it is possible to obtain (002) Cr texture from which epitaxial growth yields a (11.0) textured Co film. Since this texture calls for the HCP c-axis to lie totally in the film plane higher coercivities usually result. Less often reported, but still commonly observed, is a (10.0) Co texture which is now believed to be due to a (112) underlayer texture [17].

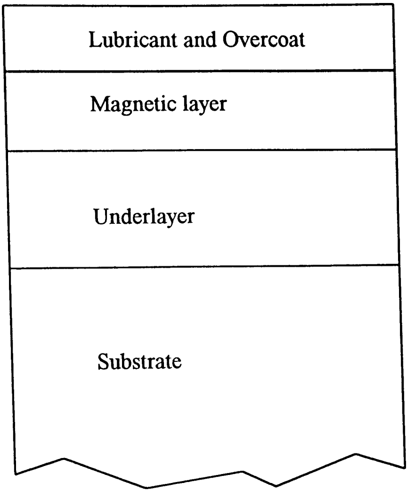

Figure 2. Traditional thin film media structure

Due to the Cr roughness and grain boundaries the Co grain size tends to replicate the Cr grain size. Hence, provided the Co grains do not grow together, and enable the Co to connect at the interfaces, the magnetic switching unit size is largely determined by the underlayer grain size. To decouple the grains and to keep the magnetic switching unit small various Co alloys have been studied to provide a non-magnetic grain boundary phase. For example, in CoCrTa and in CoCrPt, it has been argued that preparation of the films at elevated temperatures causes Cr segregation to the grain boundaries.

The most straight forward approach to increase the anisotropy is to simply choose magnetic alloys which posses higher magnetocrystalline anisotropies. However, there are not many choices among the metals. Because of the unquenched orbital angular momentum of the 4f electrons, the crystalline rare earth-transition metal alloys and compounds represent some of the best candidates. $SmCo_5$ has the largest known anisotropy energy, about 20 times greater than that of HCP Co alloys. However due to the large atomic size difference between the rare earths and the transition metals, vacuum deposition of the rare earth-transition metals films at temperatures less than 600 C usually results in an amorphous material [18] which does not possess the crystalline anisotropy value. The third disk sample studied (Figure 1) is SmCo prepared on a Cr underlayer [19] and it was found that this underlayer had induced interfacial crystallization via epitaxial growth between the (110) Cr texture and the (11.0) texture of the SmCo. Other studies [20] have found additional interfacial crystallographic relationships. Without this Cr underlayer highly exchange coupled media with low coercivities are obtained. However, with the Cr underlayer coercivities in the 3000 Oe range result and the medium noise becomes quite respectable. The noise measurements, as well as MFM imaging, of recordings on this medium indicate that it has the potential to perform at a few Gb/in^2. However, the apparent grain sizes are quite small and one would anticipate that the family of materials should perform better. D. Sellmyer et. al. [20] have investigated the microstructure and magnetic properties of both the SmCo and the PrCo material system and predicted that when annealed at 400 C the PrCo should be able to support well above 10 Gb/in^2. The addition of Pt to the HCP Co alloys appears to increase the anisotropy substantially. This is probably due to a number of resulting Co-Pt phases. By keeping the Cr content high in the CoCrPt alloy and by carefully controlling the Cr underlayer the Cr content high in the CoCrPt alloy and by carefully controlling the Cr underlayer grain size via processing conditions the media noise is kept reasonably low. Recording data is shown for a high performance experimental CoCrPt/Cr (3000 Oe) in Figure 1. It is interesting to note that out to the 300 Kfci limit of our recording system no supra-linear increase in the noise is observed. It should be noted that the lower $M_r\delta$ of this media results in smaller demagnetization field at the recorded transition and this naturally extends the useful linear density.

Peng et al.[21] recently showed that epitaxial growth alone is not sufficient to achieve high coercivity. If the grain size of the Cr underlayer is large enough and the processing conditions are such to promote cobalt alloy bi- and quad-crystal structures, then the effective magnetocrystalline anisotropy is compromised and, hence, the coercivity is degraded. Clearly the processing conditions as well as the size of the underlying Cr grain determine the number of nucleation sites for the Co growth and whether or not more than one Co orientational variant on the Cr grain results. If a higher Co mobility could be obtained via holding the substrate at a high temperature or by maintaining a very high vacuum (so that the Cr surface does not become contaminated or oxidized) and a slow deposition rate it is likely that only one orientational variant of the Co alloy would result.

One only has a limited number of non-conflicting processing variables with which to control the media properties, however more flexibility can be introduce if additional material systems and structures can be used to manipulate the thin film microstructure and hence magnetic properties. This approach has led to the search for new materials and to a new media structure. Figure 3 introduces the use of an intermediate layer and a seed layer as well as the use of new underlayer materials to achieve simultaneously smaller grains and high coercivity (anisotropy). Each of the layers can have multiple purposes, but the following gives a simplified picture of their roles: The seed layer is to provide an initial texture, while still providing a smooth surface to the underlayer. This way the underlayer texture is formed quickly. The underlayer is to control the fundamental grain size and, also, to transfer a high quality texture via epitaxial growth of the latter layers. The intermediate layer can provide both chemical effects and a buffer interface to promote a better Co layer texture as we shift from a BCC lattice to the HCP. The overlayer, overcoat, and lubricant are to provide their normal protective functions.

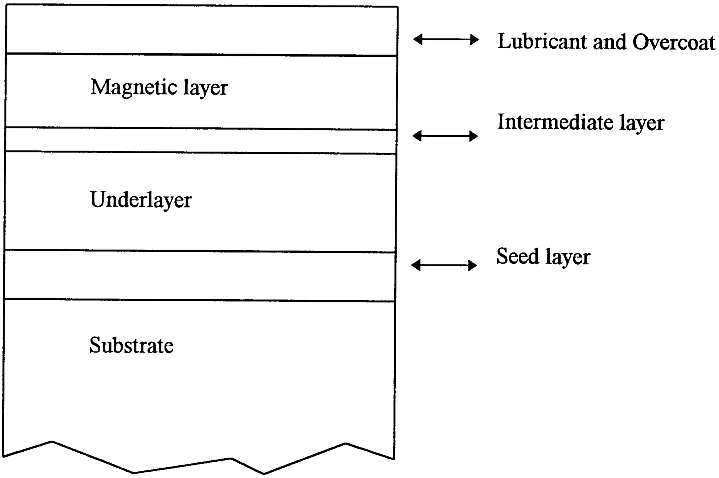

Figure 3. New multiple layer media structure

The use of Pt in Co alloys expands the Co lattice resulting in a poor epitaxial match between the Cr underlayer and the CoPt alloy. Fang and Lambeth [22] used CoCrTa as a thin (< 5 nm) intermediate layer. The CoCrTa lattice matched well to the Cr (110) and then provided an HCP template for the CoCrPt to grow upon. Coecivities well over 4000 Oe resulted. Because the two magnetic layers grow epitaxially they are exchange coupled and switch together. However, the fundamental grain size and medium noise is still largely set by the underlying Cr.

To reduce the grain size new underlayer materials could be used. The first consists of an alternative underlayer with B2-type crystal structure [17]. The B2 (CsCl) is a derivative structure of the BCC (Cr) and for NiAl or FeAl the atomic spacing is almost identical to that of Cr thus providing a potential epitaxial match for HCP Co [17]. Electron microscopy of the sputtered NiAl reveals a grain size which is more uniform and about half that of Cr [17] hence, there is the potential for smaller Co grains and lower media noise. As demonstrated in Figure 4 when CoCrPt (or CoCrTa) is deposited onto NiAl, FeAl or Cr underlayers, using identical processing conditions, very similar coercivities are obtained provided the B2 underlayer is thicker. However, if even a very thin, 2.5 nm, intermediate layer of Cr is used on the B2 underlayer then the coercivity is even greater than for the medium with a Cr underlayer. The dramatic effect of the intermediate layer is believed to be due to a smoother atomic interface resulting in a more perfect Co crystallite and higher anisotropy. X-ray diffraction data is shown in Figure 5 comparing the Cr/NiAl to the NiAl and the Cr underlayers. The last curve of Figure 1, showing the lowest medium noise, utilizes the NiAl underlayer and Cr intermediate layer. Clearly the small grain size of this underlayer has resulted in a medium with the lowest noise, 2.5 to 3 dB lower than the CoCrPt/Cr. Again no supra-linear noise behavior was observed.

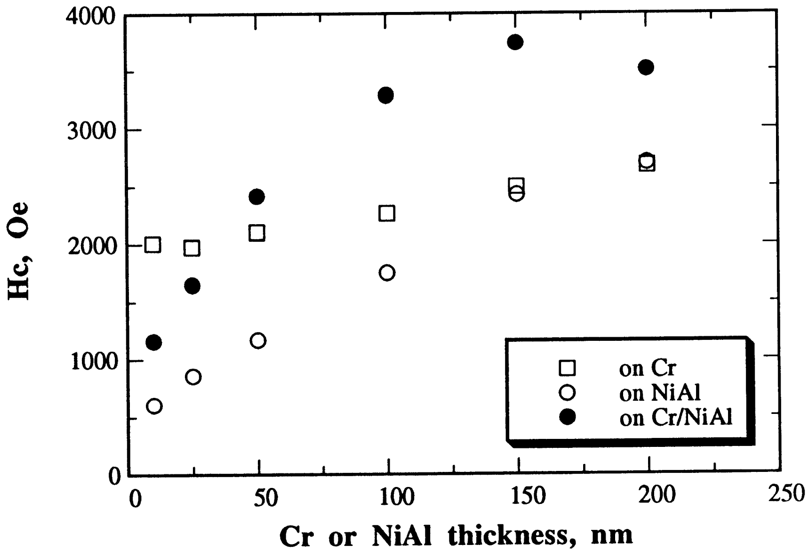

Figure 4a. Coercivity vs. underlayer thickness for CoCrPt on Cr/NiAl, NiAl, and Cr

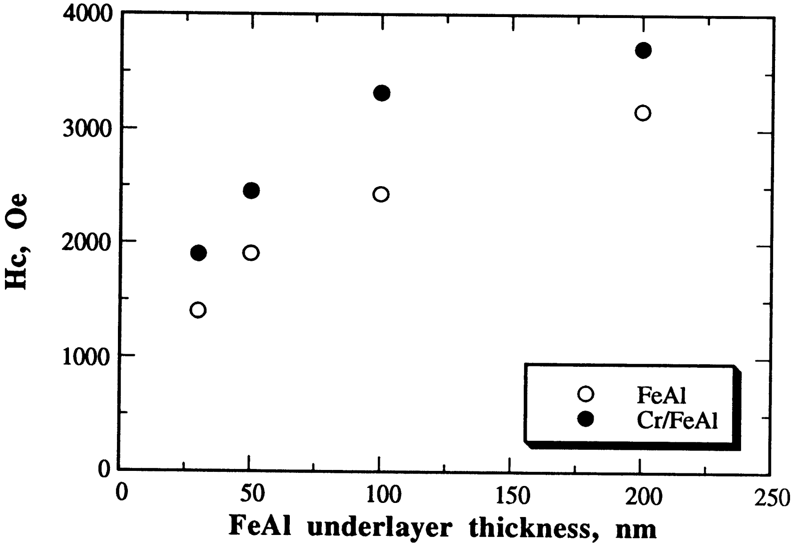

Figure 4b. Coercivity vs. underlayer thickness for CoCrPt on Cr/FeAl and FeAl

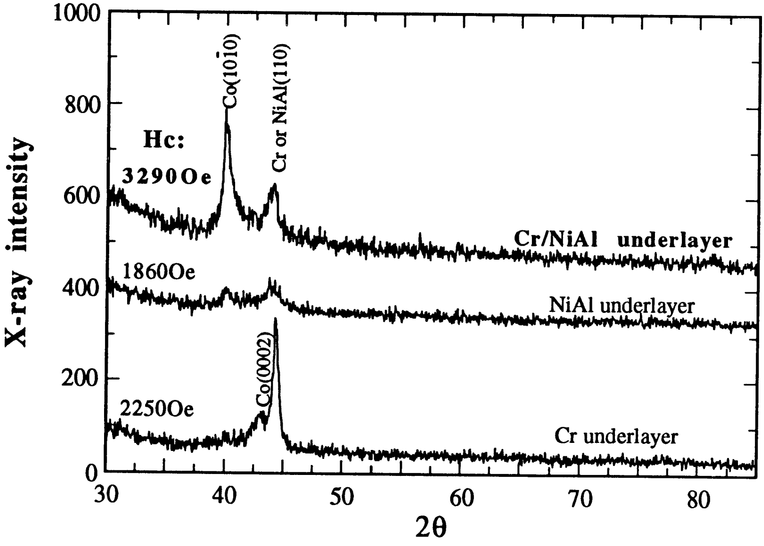

Figure 5. X-ray diffraction of CoCrPt on Cr/NiAl, NiAl, and Cr

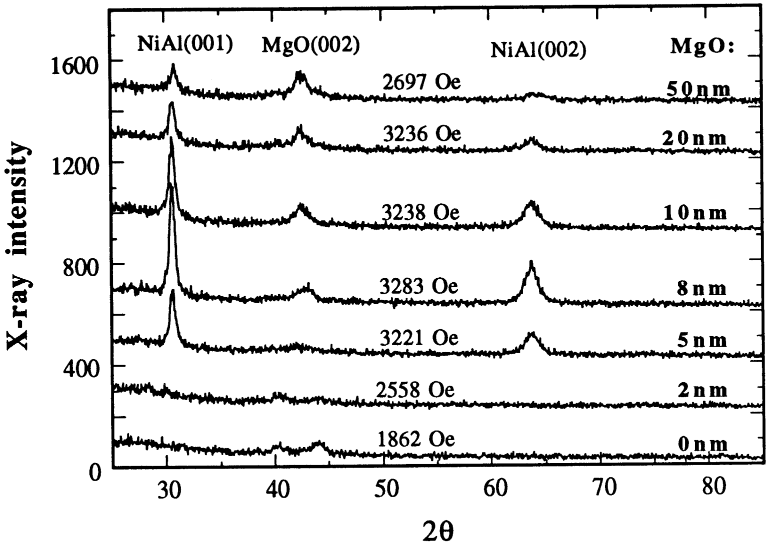

Figure 6. X-ray diffraction of CoCrPt/NiAl on sputtered MgO seed layers

The seed layer approach is used to initialize the underlayer crystal texture which may in turn enhance crystal perfection by minimizing internal lattice defects. Nakamura et al. [23] demonstrated that Cr could be epitaxially grown on single crystal [001] MgO. For this B1-type crystal the (001) planes have the lowest surface energy[24]. Hence, we have found that even very thin layers of sputtered MgO are (001) textured. This surface lattice matches well with the BCC Cr [25] and the NiAl underlayers to induce a strong (002) underlayer texture, Figure 6, even when the films are prepared without preheating the substrate. Coercivities greater than 4000 Oe have been achieved for CoCrPt magnetic layers grown on this structure[25,26].

IV. Status and Projections

By proper choice of magnetic alloy and by sophisticated control of media microstructure it appears that it will be quite possible to achieve greater than 10 Gb/in^2 areal densities. Provided the coercivity is large and the $M_r\delta$ is small so that the effect of demagnetization forces are minimized then the data should remain stable. However, it seems unlikely that 100 Gb/in^2 areal density media will be approached via these traditional techniques. The limitations to achieving these higher densities arise both from the question of data stability as the grain approaches the superparamagnetic size and because it becomes impractical to perform the lithography to make such small magnetic heads. The lower demagnetization forces associated with the required lower saturation magnetization of perpendicular recording media [27] might extend the stability regime, but it is difficult to argue that this extension could be greater than a factor of two. Fundamentally the thermal stability concern is based upon the need for a bit cell to be composed of an ensemble of random sized and oriented magnetic particles. Clearly, a bit cell were composed of a single magnetic switching unit which was large compared to the superparamagnetic limit the thermal stability concern would diminish or vanish provided domain walls do not exist inside the bit cell. The medium noise characteristics would have to be completely redefined as particle counting statistics would no longer apply. Patterning the media bit cell is a possible approach to this type of medium. Two size regimes to the patterning might be used to classify the structure. One would be to pattern the switching unit size to correspond exactly to the bit cell dimension [28]. This would require a sophisticated lithography and the cell size will be well beyond conventional lithography limits. Perhaps direct electron beam lithograph could be used to demonstrated the concept but other less expensive techniques would need to be developed for mass production. A second regime might call for making each switching unit size just larger than the super-paramagnetic limit size. For example, uniformly spaced and oriented cells might be formed on 10 nm centers by some technique involving self assembly. Figure 7 demonstrates the concept where a bit cell could be formed from a discrete number of the switching unit cells. Clearly for the patterned medium noise becomes more of an issue of medium perfection or of transducer registration.

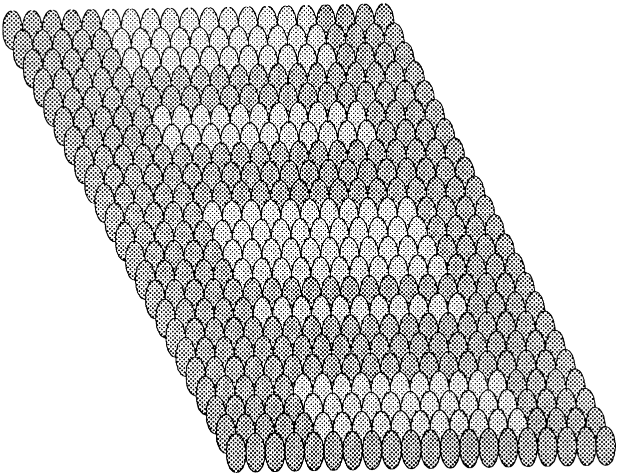

Figure 7. Schematic of self-assembled pattern media

Assuming that a method could be developed to construct a self assembled patterned medium and that a probe transducer such as used in MFM imaging could be extended to resolve the proposed 10 nm particle, then it appears that areal densities approaching 6000 Gb/in^2 might be achievable. It is also clear that in order to prevent magnetostatic interactions from creating randomness in the data either the coercivity must be large or the magnetic moment must be kept small. Thermomagnetic magneto-optic recording is based on deviating from the compensation point only to record or to playback. Since there is no net magnetic moment at the compensation point this configuration is inherently stable against demagnetization enhanced by thermal fluctuations. If the medium is patterned, registration between the transducer and the bit cell is still an issue; however, if the medium is not patterned, but is continuously uniform (without grain structure) and highly exchange coupled, the bit cell location will only be determined by the resolution of the transducer field. Patterning regular fluctuations in the media anisotropy, on an atomic scale, could possibly alleviate some of the need for an extremely sharp transducer field. Clearly the orientation of the media needs to be fixed if the transducer has a fixed orientation otherwise the transducer will be ineffective on those moments which are orthogonal to the transducer field. Perpendicular orientation may be the most straight forward choice as the orientation is determined by the substrate. On the other hand if the medium is developed on an oriented substrate such as a single crystal of Si then the orientation could conceivably be in the substrate plane. Optical near field recording has been proposed as a transducer scheme [29] and demonstrated to record up to 45 Gb/in^2. Here the tip of an optical fiber was drawn to a small diameter to aperture the light coming from (playback) or going to (recording) the medium. It is conceivable that if the tip size were reduced to a few tens of nanometers that it could be used with either the proposed continuously uniform exchange coupled medium or the patterned medium. In any of these probe based storage systems the transducer noise must be kept small compared to the viable media signal. It appears that MFM provides a demonstrable proof that for long integration times the noise can be averaged out. Hence, it may be that the trade-off between data rates and data reliability will play an even more critical role than in the past. For near field recording the signal is proportional to the photon flux [30] and the biggest concern may prove to be that the media does not over heat during readout. This will most likely be determined by the required phonon flux necessary to overcome any probe noise.

V. Summary

Clearly there are many future possibilities for continuing the rapid pace of increasing data storage densities. Here we have tried to outline a philosophy and some of the near term options for improving hard disk media performance without radical changes in how magnetic disk recording is currently performed. In addition, some of the current thoughts on how to extend recording densities beyond the tens of Gb/in^2 were briefly discussed. There does not appear to be a fundamental limit to magnetic recording densities until the bit cell approaches the size of an individual superparamagnetic particle. However, the engineering path to achieve such recording densities awaits the adventurous.

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References:

1. J. L. Simonds, “Magnetoelectronics Today and Tomorrow”, *Physics Today*, **48**, 26 (1995).
2. T. Yogi, C. Tsang, T. A. Nguyen, K. Ju, G. L. Gorman and G. Castillo, "Longitudinal Media for 1 Gbit/in^2 Areal Density," *IEEE Trans. Magn.*, **MAG-26**, 2271 (1990).
3. M. Futamoto, F. Kugiya, M. Suzuki, H. Takano, Y. Matsuda, N. Inaba, Y. Miyamura, K. Akagi, T. Nakao, H. Sawaguchi, H. Fukuoka, T. Munemoto, and T. Takagaki, "Investigation of 2 Gbit/in^2 Magnetic Recording at a Track Density of 17 kTPI," *IEEE Trans. Magn.*, **MAG-27**, 5280 (1991).
4. C. Tsang, D. McCown, H.A. Santini, J. Lo and R.E. Lee, "3 Gb/in^2 demonstration with dual element heads and thin film disks", *IEEE Trans. Magn.*, **MAG-32**, 7 (1996).
5. E. S. Murdock, R. F. Simmons, and R. Davidson, "Roadmap for 10 Gbit/in^2 Media: Challenges," *IEEE Trans. Magn.*, **MAG-8**, 3078 (1992).
6. J. A. Brug, T. A. Anthony and J. H. Nickel, “Impact of new magnetoresistive materials", *J. Appl. Phys* **79**, 4491 (1996).

7. M. L. Williams and R. L. Comstock, "An analytical model of write process in digital magnetic recording", AIP Conf. Proc., 5, 738 (1972).
8. R. A. Baugh, E. S. Murdock and B. R. Natarajan, "Measurement of Noise in Magnetic Media," *IEEE Trans. Magn.*, **MAG-19**, 1722 (1983).
9. N. R. Belk, P. K. George, and G. S. Mowry, "Noise in High-Performance Thin-Film Longitudinal Magnetic Recording Media," *IEEE Trans. Magn.*, **MAG-21**, 1350 (1985).
10. M. J. Freiser, "On the Zigzag form of charged domain walls", *IBM J. Res. Dev.*, **23**, 330 (1979).
11. K. E. Johnson, E. Y. Wu, D. C. Palmer, J. G. Zhu, "Media Noise Improvement Through Head-Disk Spacing Reduction", *IEEE Trans. Magn.*, **MAG-28**, 2713 (1992).
12. P-L. Lu and S. H. Charap, "Thermal instability at 10 Gb/in^2 magnetic recording", *IEEE Trans. Magn.*, **MAG-30**, 4230 (1994).
13. J. Daval and D. Randet, "Electron Microscopy on High-Coercive-Force Co-Cr Composite Films", *IEEE Trans. Magn.*, **MAG-6**, 768 (1970).
14. Y. C. Feng, D. E. Laughlin and D. N. Lambeth, "Formation of Crystallographic Texture in RF Sputter-Deposited Cr Thin Films," *J. Appl. Phys.*, **76**, 7311, (1994).
15. D. E. Laughlin and B. Y. Wong, "The Crystallography and Texture of Co-Based Thin-Film Deposited on Cr Underlayers," *IEEE Trans. Magn.*, **MAG-27**, 4713 (1991).
16. T. Lin, R. Alani and D. N. Lambeth, "Effects of Underlayer and Substrate Texture on Magnetic Properties and Microstructure of a Recording Medium", *J. Magn. Mag. Mater.*, **78**, 213 (1989).
17. L-L. Lee, D. E. Laughlin and D. N. Lambeth, "NiAl Underlayers for CoCrTa Magnetic Thin Films," *IEEE Trans. Magn.*, **MAG-30**, 3951 (1994).
18. F. J. Cadieu, T. D. Cheung, L. Wickramasekara, N. Kamprath, H. Hegde and N. C. Liu, "The magnetic properties of high H_c Sm-Co, Nd-Fe-B, and Sm-Ti-Fe films crystallized from amorphous deposits", *J. Appl. Phys.*, **62**, 3866 (1987).
19. E. M. T. Velu and D. N. Lambeth, *IEEE Trans. Magn.*, **MAG-28**, 3249 (1992), Also, D. N. Lambeth, E.M.T. Velu, G. Bellesis, L. L. Lee, and D. E. Laughlin, "Media For 10 Gb/in^2 Hard Disk Storage: Issues And Status", *J. Appl. Phys.* **79**, 4496 (1996).
20. Y. Liu, D. J. Sellmyer, B.W. Robertson, S. S. Shan and S. H. Liou, " High resolution electron microscopy and nano-probe study of SmCo/Cr films", *IEEE Trans. Magn.*, **MAG-31**, 2740 (1995), Also, D. J. Sellmyer and Z. S. Shan, "Magnetic Hysteresis in Novel Nanostructured Films", These Proceedings.
21. Q. Peng, H. N. Bertram, N. Fussing, M. F. Doerner, M. Mirzamaani, D. Margulies, R. Sinclair, and S. Lambert, "Micromagnetic and Experimental Studies of CoPtCr Polycrystalline Thin Film Media with Bi-crystal Microstructure," *IEEE Trans. Magn.*, **MAG-31**, 2821 (1995).
22. L. Fang and D. N. Lambeth, "A New High Coercivity Cobalt Alloy Thin Film Medium Structure for Longitudinal Recording", *Appl. Phys. Lett.*, **65**, 3137 (1994).
23. A. Nakmura and M. Futamoto, *Jpn. J. Appl. Phys.*, **32**, **Pt. 2**, 10A, L1410, (1993).
24. P. W. Tasker, "Surfaces of magnesia and alumina", *Adv. Ceram.*, **10**, 176 (1984).
25. L-L. Lee, B. K. Cheong, D. E. Laughlin and D. N. Lambeth, "MgO Seed Layers of CoCrPt/Cr Longitudinal Magnetic Recording Media", *Appl. Phys. Lett*, **67**, 3638 (1995).
26. L-L. Lee, D. E. Laughlin and D. N. Lambeth, "Seed layer induced (002) crystallographic texture in NiAl underlayers", *J. Appl. Phys.*, **79**, 4902 (1996).
27. S. Iwasaki, "Perpendicular Magnetic Recording," *IEEE Trans. Magn.*, **MAG-16**, 71 (1980).
28. R. M. H. New, R. F. W. Pease and R. L. White, "Submicron patterning of thin cobalt films for magnetic storage", *J. Vac. Sci Technol. B*, **12**, 3196 (1994).
29. R. E. Betzig, J. K. Trautman, R. Wolfe, E. M. Gyorgy, P. L. Finn, M. H. Kryder and C-H. Chang, "Near-Field Magneto-Optics and High Density Data Storage," *Appl. Phys. Lett.*, Vol. 61, (2), 142 (1992).
30. J. E. Hurst, D. Weller and H. A. Notarys, "Short Wavelength MO Recording: System Noise Issues and Performance Optimization," *J. Magn. Soc. Jpn.*, Vol. 17, Supp. No. S1, 299 (1993).