FUTURE READ CHANNEL TECHNOLOGIES AND CHALLENGES FOR HIGH DENSITY DATA STORAGE APPLICATIONS

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ABSTRACT

The goal of this paper is to give a brief description of the data storage technologies that are expected to appear in the near future, and the challenges these new systems bring to designing robust read channels. We focus on perpendicular, heat assisted magnetic recording and probe storage systems.

1. INTRODUCTION

The data storage density has increased by a factor of more than 50 million since the introduction of the first commercial disk drive in 1957 as part of the IBM RAMAC system. Most of this increase is due the improvements in head, media, read channels and mechanical components of a drive. The introduction of Partial Response Maximum Likelihood (PRML) read channels and Magneto-Resistive (MR) heads as well as better thin films doubled the rate of increase in the areal storage density from 30% compound annual growth rate (CAGR) to 60% CAGR after 1992. This rate has peaked around 130% CAGR around year 2000 after the introduction of Giant Magneto-Resistive (GMR) heads (see Chapter 1 in [1]). The classical metric (among many others) for data storage products is the areal density which can be expressed as

$$\mathrm{ArealDensity[bits/inch^2]} = \frac{\mathrm{1bit}}{a\mathrm{[inch]}w\mathrm{[inch]}} \qquad (1)$$

where a and w are the lengths along the on-track and off-track directions, respectively, of the specific area of interest to be magnetized. Today areal densities larger than $100Gb$ per square inch have been shown by various research teams around the globe. Historically most of the gains in areal density have been achieved by scaling. For example, by reducing the dimensions a and w in Eq. 1 by a factor of 2, the areal density will increase by 4 times. As the dimensions become smaller and smaller, it becomes harder to build media, heads, and read channels that will provide a reliable data storage system.

In this paper, we briefly introduce possible technologies that are being worked at to enable further increases in data storage densities. In Section 2 we focus on perpendicular and heat assisted magnetic recording (HAMR) systems, which try to leverage on a disk based storage system. In Section 3 we talk about a new storage system called probe storage which tries to fill in the gap between traditional semiconductor memory and hard disk drive systems. In each section we outline the main challenges facing the read-write engineers while designing robust channels for these emerging technologies. Finally in Section 4 we conclude the paper.

2. DISK DRIVE BASED FUTURE RECORDING SYSTEMS

Today's conventional magnetic recording architectures are based on longitudinal magnetic recording principles, where magnetization is directed in opposite orientations along with the moving direction of the recording head. The goal of a read channel designer is to develop encoding and precompensation algorithms for write process, and analog front end, synchronization, equalization, detection and decoding algorithms to be employed during the read process.

The noisy readback signal $r(t)$ in magnetic recording channels can be expressed in terms of the bit sequence c_k and transition response $g(t)$ as

$$r(t) = \sum_{k=-\infty}^{\infty} d_k g(t - kT + \Delta t_k) + n(t) \qquad (2)$$

where Δt includes the effects of transition jitter noise, and $n(t)$ represents the additive white Gaussian noise. In this equation $d_k = c_k - c_{k-1}$ and $c_k \in \{0, 1\}$. For longitudinal recording, the transition response is usually modelled as a Lorentzian pulse [2] $g(x) = \frac{K}{1+(2x/ND)^2}$ where x is a time index normalized by the channel clock T, K is a scaling constant, and ND = PW_{50}/T is a normalized recording density. PW_{50} determines the width of the longitudinal transition response at 50% of its peak value. The impulse response of longitudinal recording channel can be obtained by taking the derivative of the transition response. The frequency response of the impulse response is plotted in Fig. 1, where clearly we can see a frequency null at the origin. Such a frequency null constitutes the major difference between channel design for longitudinal recording and

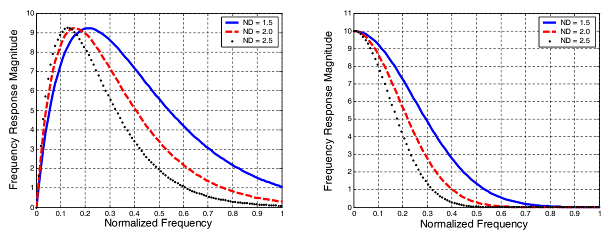

Fig. 1. Impulse response of longitudinal (left) and perpendicular (right) magnetic recording normalized frequency domain (normalized to sampling frequency).

perpendicular recording, a recording technology introduced in the next section.

2.1. Perpendicular Recording

If we keep increasing areal density of magnetic recording system, the granularity of the medium becomes more important. In reality there are many tiny grains of magnetic material of volume V within the medium, each with their own uniaxial anisotropy coefficient K_u. The larger K_u, the harder to change its magnetization direction. The anisotropy energy for those particles is given as $E_P = K_u V$, and represents energy barrier for partial stability. This energy barrier should be much larger than the thermal energy $E_T = k_B T$ (where k_B is the Boltzmann's constant and T is the temperature). Another way of expressing this is to have the constraint $(K_u V)/(k_B T) \geq M$ where M is a large number, like 60. This equation puts a limit on our ability to increase areal density by scaling. This is called super paramagnetic limit [3], and determines the maximum areal density we can achieve for fixed K_u and T.

One way of further increasing the areal density by scaling might be reducing the volume of grains V while increasing K_u at the same time in equation $E_P = K_u V$. As K_u is proportional to the coercivity of the medium H_c, increasing K_u means increasing H_c, which necessitates larger applied head fields to magnetize the grains in order to store the bit of information. Perpendicular recording can double the available write field over longitudinal recording by effectively placing the medium in the narrow gap formed between write pole and soft magnetic underlayer (see Chapter 4 in [1]). Subsequently, the magnetization orientation of the media becomes perpendicular to the scanning direction of the magnetic head. We can summarize the advantages of perpendicular recording over longitudinal one as (see Chapter 2 in [1]):

- Writing and read-back are less dependent on the film thickness; which in turn provides higher areal density without compromising thermal stability.
- At the same linear density, perpendicular recording provides a larger read-back signal.
- The write head field gradient can be larger in the perpendicular recording, which yields a smaller transition jitter and no DC particulate noise.
- The demagnetization field decreases with increasing linear density.

We can model the isolated transition response of perpendicular recording as an error function, $g(x) = erf(\sqrt{S}x)$, where x is a time index normalized by the channel clock T, $S = 4\ln 2/\mathrm{ND}^2$, and $erf(\cdot)$ is an error function which is defined by $erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt$. Normalized recording density is again expressed as $ND = PW_{50}/T$ but here PW_{50} determines the width of the impulse response at 50% of its peak value. The corresponding impulse response can be obtained from the transition response by taking its derivative. Again, the frequency response of perpendicular impulse response is plotted in Fig. 1 for different ND values.

2.2. Heat-Assisted Magnetic Recording (HAMR)

As described earlier, the superparamagnetic limit together with maximum attainable head field in a system specifies the maximum areal density of the system. Recently, HAMR (Heat Assisted Magnetic Recording) has been proposed to increase the areal densities beyond the practical limitations of the conventional recording architectures. The principles of HAMR, also known as hybrid recording, are based on 1) choosing a medium with very high coercivity H_c, or equivalently K_u, to ensure that the medium still satisfies the superparamagnetic limit with very small grain volumes V; 2) reducing the coercive field during the write process by heating the medium, for example with a focused laser beam [4]. When the medium is heated, its coercivity is reduced mak-

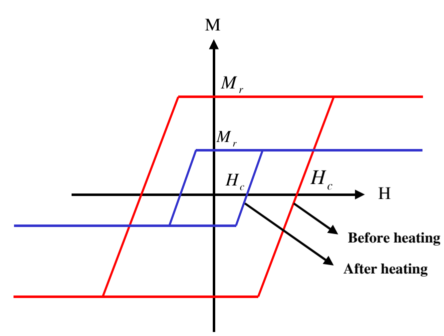

Fig. 2. Idealized magnetization versus magnetic field hysteresis loop (MH loop) of the medium before and after heating

ing writing possible. Then, after writing the bit, the medium cools back to its original temperature with high coercivity H_c (or high K_u) allowing the medium to be thermally stable. The idealized version of the MH hysteresis loop before and after heating the medium is shown in figure 2.

Although the idea of HAMR might sound simple, it has its own implementation issues. For example, if we are targeting an areal density of 1 Terabit per square inch, then the average bit area will be $(25nm)^2$. Assuming the Bit-Aspect-Ratio (BAR) to be 1 and head linear speed relative to medium to be 25 m/s, we will obtain the bit time to be 1ns. In other words, the heating and cooling mechanism of the bit cell in HAMR recording has to be done within 1ns. Supplying a temperature difference ΔT, for example of 300K-400K, within 1ns of time to a spot with diameter 25nm creates a number of major issues.

The joint optimization of temperature and magnetic components in a HAMR system is a very challenging task, and there are very crucial problems to be solved before its commercialization. Still, because of its enormous advantages in increasing the areal density, HAMR specific issues are taken into consideration one by one, and recently a thermally assisted recording architecture was reported with an areal density equal to 400 Gigabits per square inch [5]. The more issues which are resolved, the larger the areal densities which will be reported.

2.3. Challenges in read channel design for perpendicular recording and HAMR

From the perspective of read channel design both perpendicular and HAMR technologies pose a set of challenges that needs to be dealt with. These challenges include but not imited to:

Low SNR: Although both systems are expected to improve write-read processes, it is also expected that a significant portion of the performance gain needs to be provided by read channel algorithms. Designing timing and analog front end algorithms that can function in very low SNR conditions is a very challenging task. For example, as the SNR decreases the cycle slip rate (the rate timing skips a bit) increases and single handedly makes the overall system nonoperational.

Signal Shapes: One of the determinants of the robust channel design is the type of signals that one must deal with. For example, as shown in Fig. 1, significant DC and low frequency components are present in perpendicular recording readback signals. This entails significant changes in channel architecture design from conventional longitudinal recording, where DC is absent from the readback signal. Due to the high-pass pole presented in analog front end (AFE) circuit, the baseline of readback signals can wander, commonly referred to as baseline wandering. While longitudinal recording channels can be designed to be insensitive to baseline wandering due to its DC null, this is not the case for perpendicular recording, where considerably amount of signals are contained in the low frequency region. As such, proper measures in AFE as well as code design are called for to mitigate the baseline wandering effect in perpendicular recording channel design.

Noise and Nonlinearities: While most of the noise that affects longitudinal systems is electronic noise, perpendicular (and most probably HAMR) systems are dominated by media (position jitter) noise. This noise is not Gaussian, not additive and is pattern dependent. Also the type and the strength of nonlinearities seen in both perpendicular and HAMR systems are quite different than longitudinal ones. Therefore one needs to design special cancellation algorithms as well as unique pattern dependent detectors to handle these impurities.

Codes: There will be a need to design both constrained codes to handle the spectral differences and timing constraints, as well as high gain giving codes that can operate at low SNR regimes.

Error Correction and Recovery Systems: As perpendicular and HAMR push the areal density ever higher, the system designer will have to ensure reliability (generally measured in terms of sector failure rate) at par or better levels than longitudinal. Given this, the importance of designing powerful error correction and recovery systems becomes apparent.

3. PROBE STORAGE

The motivation behind probe storage is to fill the gap between traditional semiconductor memory (e.g., dynamic random access memory (DRAM)) and hard-disk drive based storage in the memory hierarchy. This gap is due to the different physical characteristics of semiconductor memory and disk drives. In particular, while disk drives can provide enormous amount of storage capacity at very low cost, the access latency is only improving marginally over the years, lagging behind DRAM by close to two orders of magnitude. On the other hand, while DRAM can provide fast access to data, its manufacturing difficulties keep the cost-per-Gigabyte far above disk drives.

To reduce the latency of hard disk drives, where usually a single read head seeks data from a rotational media disk, a parallel of active read heads can considerably lower the seeking time of disk drives, since the average travelling distance of the read head to reach a desired location in the media is reduced. Furthermore, rotational access method can be replaced by a linear matrix scheme where the heads (a.k.a. probe tips, cantilevers) move in a linear fashion relative to the media. Fig. 3 depicts an artist's rendering of a probe device. Notice that there are many probe tips above the storage media. Moreover, by employing paral-

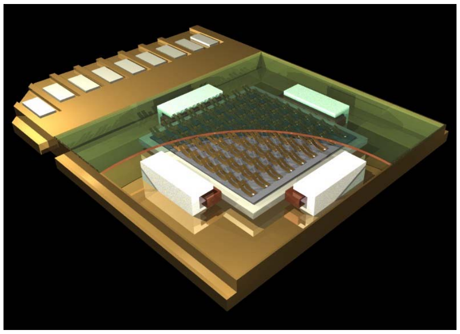

Fig. 3. Artist's rendering of probe device (courtesy of Mark Lutwyche of Seagate Research)

lel probe tips, the data rate required for each head can be significantly lowered, which makes many reading/writing mechanism that was not practical for single-head disk drives due to their excessive latency become feasible. For example, although one can still use traditional magnetic recording techniques for reading and writing [6] in probe devices, more promising approaches include the phase-change material presented in [7] and the thermal-mechanical approach reported by IBM [8]. These new materials and the associated reading and writing mechanism provide additional avenues to bypass the superparamagnetic limit facing the magnetic recording industry today.

Read channel design for probe storage devices, however, becomes very challenging mainly due to massive parallel operation of probe read heads as well as novel physical reading/writing mechanisms different from traditional magnetic recording. Clearly the read channel designers will be dealing with all the general issues listed before for perpendicular and HAMR systems. In addition to these there are some unique challenges we describe below.

- In view of parallel operation of probe tips, the read channel of probe device can be considered as a multi-input-multi-output channel. Potentially, one can exploit the interactions among the input and output signals from multiple tips to improve system performance, just as the case for multiuser wireless communication channels.

- A second challenge of probe channel design lies in the complexity limitation of the signal processing and coding algorithms. Due to the massive parallelism of active channels (in the order of hundreds or even thousands) existing in a single probe device, practical cost and power consumption limits the complexity of each individual channel.

- Thirdly, read channel architecture for probe device should be designed to accommodate faulty probe tips. In other words, more robustness is required for probe channel than traditional magnetic recording channel.

- Finally, extra care is needed during probe channel design to address the imperfectness associated with each individual read/write mechanism. Such examples include nonlinearities, baseline wandering, and transition jitter noise, to name a few.

4. CONCLUSION

In this paper we briefly described the data storage technologies that are expected to appear in the near future. In first part of the paper we focused on disk drive based systems such as perpendicular and HAMR as alternatives to the current longitudinal recording read-write mechanism. Later we looked at probe technology which tries to fill the gap between hard drives and semiconductor memory. In each case we described the possible challenges that each system presented in terms of read channel design.

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