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TOPICAL REVIEW

Ultimate limits to thermally assisted magnetic recording*

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Abstract

The application of thermal energy to enable recording on extremely high anisotropy magnetic media appears to be a viable means of extending the density of stored information. The central physical issue facing the technology is what gain can be realized in writability along with long-term data stability using imaginable media materials. We reasonably expect the material properties $M(T)$ and $H_k(T)$ to determine this, since a stability metric for media with characteristic magnetization switching unit volume V is $MVH_k/2k_BT$. This matter is controversial owing to still open questions related to thermomagnetic recording with temperature elevation above the Curie point and optimal cooling rates. There are indications that multi-component magnetic media may offer advantages in achieving performance goals. Beyond the physical issues lie engineering matters related to the correct system architecture to yield a practical storage device to meet future customer expectations. Here one must address a detailed means of delivering localized heating to the magnetic medium to perform efficient recording. To date, magnetic recording devices have been highly mechanical systems, so it is natural to inquire how a need for an aggressively heated head–medium interface could impact the evolution of future systems. Eventually elements of thermally assisted recording could be combined with patterned media approaches such as self-organized magnetic arrays to push toward ultimate limits where the thermal instability of bits overtakes engineered media materials. Finally, a practical recording system cannot be realized unless a means of finding, following, and reading the smallest bits with a usable signal-to-noise ratio exists—engineering issues separate from an ability to reliably record those bits.

(Some figures in this article are in colour only in the electronic version)

* This paper is based on an invited presentation of the same title given at the meeting of the American Physical Society, 22–26 March 2004, in Montreal, Quebec, Canada.

Contents

1. Introduction

Magnetic recording was invented over one hundred years ago. Since the 1950s the technology has enjoyed a golden age of exponential growth in performance and utilization. While Moore's law from the semiconductor industry is the most frequently cited metric for information technology advance, magnetic recording has exhibited equally impressive advances in storage (areal) density (AD) and cost reduction [1]. Figure 1 illustrates this. In both fields, adherence to geometrical scaling is a guiding principle in this advance. A characteristic dimension of the device is reduced by a scaling factor in each successive time interval over an extended period of time, resulting in the trend depicted in figure 1. In a complex engineering system, such scaling may be sustainable over only a limited time interval, after which one or more components of the system must be replaced. Such technological transitions have certainly occurred several times in magnetic recording over the nearly half-century history in figure 1, and this often shows up as an abrupt slope change reflecting an altered growth rate. A notable example is the introduction of magneto-resistive reading head technology around 1990, and this initiated an extended period of more than a decade of accelerated AD growth at two to three times the historical Moore's law growth rate.

It is apparent that, in a finite world, exponential growth trends are not forever. When a technology matures and certain physical limits are encountered, growth trends are impacted. This has occurred in magnetic recording in the past few years as the limit of thermal stability of the constituent magnetic particles of the storage medium has been approached for the first time in the history of the technology. There was no surprise in this development, as the underlying theory of superparamagnetism [2] has been well established since the development of quantum mechanics. For a single domain magnetic particle of volume V to hold its magnetic polarization in the face of thermal agitation requires that its magnetocrystalline anisotropy energy KV far exceed the characteristic thermal energy k_BT, that is $KV \gg k_BT$. A typical criterion for the desired data storage lifetime is $\eta_0 \equiv KV/k_BT > 50$–$80$. Anisotropy energy density is a parameter determined by the storage medium material selection, while V scales downward as the recorded bit area on the medium surface shrinks under the constraint of holding the number of magnetic particles per bit N high enough to sustain adequate playback signal-to-noise ratio (SNR), since the SNR usually scales as $N^{2/3}$ to N^1. Logic suggests that the design engineer should compensate shrinking V with a choice of higher K. However, K cannot be elevated at will to maintain η_0, because the output magnetic field of the inductive heads required to record a magnetic medium must scale commensurately with the medium mean switching field, which in turn scales in proportion to K. Because the output field of a head reaches a hard material limit of the highest saturation magnetization values found in magnetic solids, $M_s \sim 2.5\ \mathrm{T}/\mu_0$,

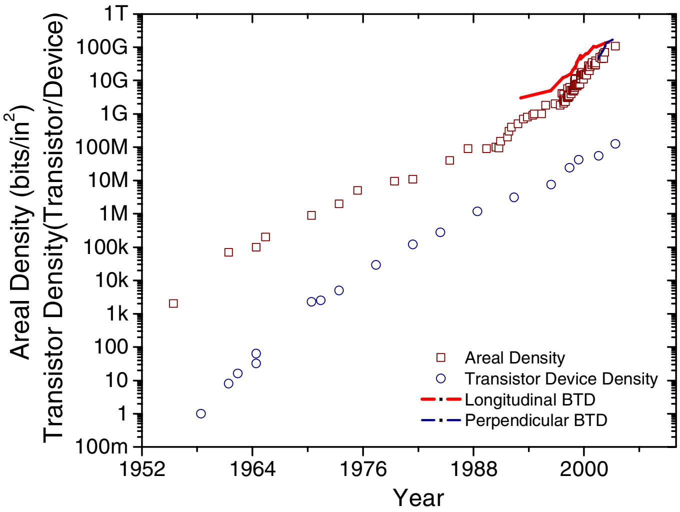

Figure 1. Magnetic recording areal density growth along with transistor count per integrated circuit device (Moore's Law) from the 1950s to the present. 'BTD' in the last two legends are laboratory technology demonstrations.

the value of the medium K at the instant of recording is strictly limited by the capability of recording heads.

This situation suggests a strategy in which the temperature dependence of K might be used to advantage. The anisotropy energy of ferromagnetic materials always drops toward zero as the material temperature is increased toward the Curie temperature T_c. The Curie temperature of recording media materials, usually alloys containing Fe, Co, and/or Ni, is typically at least a few hundred kelvins above room temperature. Supposing that $K(T)$ for the medium falls monotonically from a high value at ambient temperature to zero at T_c, one can anticipate that $\eta(T) = K(T)V/k_B T$ could be varied from a condition of extreme media stability at ambient temperature to a very small or zero value at an elevated medium temperature. In such a situation, if the medium can be locally heated momentarily during recording, the writability and the thermal stability issues could be solved simultaneously. This process is called *thermomagnetic recording*, and it is a well-established process in magneto-optic recording, a form of erasable optical data storage that has been in commercial production since the 1980s [3].

Thermomagnetic recording is also known variously as hybrid recording, thermally assisted magnetic recording, or heat assisted magnetic recording (HAMR). In recent years, the HAMR process has received increased attention in the technical literature [4]. HAMR is now recognized as one of the viable means for extending the historical growth of magnetic recording past the limitations of thermal stability in conventional ambient temperature recording. The objective of this paper is to consider some of the fundamental physical (as opposed to engineering) factors that establish the ultimate limits on data storage performance utilizing HAMR. In section 2 we will look more closely at the nature of thermal stability in magnetic particles, followed by an examination of magnetic configurations for data storage and the link to areal density in section 3. Here we consider the importance of the SNR for recording performance, and the central factors governing the SNR in the various recording configurations. Section 4 considers the issues surrounding heating the recording medium on a local scale to support high density recording. In section 5 we point to a few of the engineering issues associated with ultrahigh density data storage, including data rate, data readout, servoing, and the head–disk interface. Section 6 identifies some of the theoretical and modelling tools that are helpful in assessing high density HAMR. Finally, in section 7 we present estimates of ultimate physical limits on recorded areal density in surface (not volumetric) recording.

2. Thermal stability of single domain magnetic particles

Magnetic recording media have traditionally been composed of a closely packed ensemble of ferromagnetic particles, usually and ideally with single domain magnetization. This has been true from the earliest days of magnetic tape media through the history of magnetic disks, with either flexible or rigid substrates. From the 1940s to the 1980s, the particle ensemble was achieved by dispersing suspended particles in a volatile liquid carrier, and coating this suspension onto a substrate in a thin, uniform layer. This material was often compared to a paint-like pigment. The aim was to achieve a uniformly thick layer of well-dispersed, closely packed particles rigidly fixed in a binder. If the particles had a non-spherical shape, then a preferred orientation of the particle long axes might be desired to maximize recording performance. Such particles were often developed with a preferred magnetization orientation nearly parallel to the particle's long axis via some combination of shape and magnetocrystalline anisotropy.

Intensive development of dry thin film deposition techniques (sputtering, plating, evaporation) in the 1970s and 1980s resulted in the gradual displacement of wet coating application for magnetic media. Dry deposition offered attractive advantages for achieving better playback signal performance through a higher packing fraction arrangement of high magnetization metallic particles. The goals of retaining magnetically independent particles with a narrow size distribution in a coating with the smoothest possible surface persisted from the earliest days of recording. Controllable particle decoupling and uniform size are important aspects of achieving low noise (signal variance) in recording. Relative motion between a closely spaced recording transducer (head) and the recording medium is essential for fast, efficient, high resolution writing and reading, and the smoothness of the interface is of primary importance in minimizing component wear over the life of the recording device.

Assuming that the magnetic particles are chemically stable and protected from corrosion, the physical stability of induced magnetization in the particle ensemble that resides in the thermal environment of the recording medium is a further essential requirement. We noted in the introduction that a criterion for this stability is related to the ratio η of magnetocrystalline anisotropy energy to characteristic thermal energy. The essence of Stoner–Wohlfarth (SW) and Arrhenius–Neél–Brown (ANB) theory for the static and dynamic behaviour of particle magnetization with regard to reversal and decay is somewhat more involved [5] than specifying η, and we will show a few of the key relations here.

For simplicity, we consider the most common situation governing the particles of recording media, whereby their magnetic anisotropy is uniaxial. The SW theory concerns rotational magnetization switching induced by an applied magnetic field in ellipsoidal, single domain particles whose anisotropy axis is aligned with the primary symmetry axis. The particle's magnetization is assumed to be saturated. Expressing the particle's magnetic energy in terms of the angular orientation of the magnetization (angle θ) and applied field (angle ϕ) relative to the particle's symmetry axis (called the 'easy axis'), one is prepared to develop both the SW and the ANB analyses. Equation (1) shows that the particle's energy is composed of anisotropy and Zeeman energy terms.

$$E(\theta, \phi) = KV\left[\sin^2\theta - 2\frac{H_{\text{eff}}}{H_k}\cos(\phi - \theta)\right], \qquad \text{where}$$

$$H_{\mathrm{eff}} = H_{\mathrm{appl}} + H_{\mathrm{d}} + H_{\mathrm{ex}} \quad \text{and} \quad H_k = \frac{2K}{M_{\mathrm{s}}}. \tag{1}$$

It is common to see a plot of this relation over $0° \leqslant \theta \leqslant 180°$ for $\phi = 0$ in textbooks. When H_{eff} is zero, the Zeeman term is absent, and we have a sine squared function with minima at $\theta = 0°$ and 180°. As H_{eff}/H_k grows toward unity, one minimum continuously becomes shallower until it vanishes, while the other minimum deepens. For $H_{\mathrm{eff}}/H_k > 1$, there is just a single energy well, as the Zeeman energy due to the applied field overwhelms the anisotropy energy associated with an anisotropy field. Our physical picture then is of a fixed magnetic particle whose magnetization rotates in a single or double energy well, depending on the strength of the applied field. When a double well exists, the deeper minimum is the stable state for M aligned with the applied field, and the shallower minimum is a metastable state for M anti-parallel with H_{eff}. These two wells are separated by an energy barrier whose height relative to the respective minima can be approximated by the expression

$$E_B^{\pm}(H_{\mathrm{eff}}, \phi) \cong KV\left[1 \mp \frac{|H_{\mathrm{eff}}|}{H_0(\phi)}\right]^m, \qquad \text{where } m \cong 0.86 + 1.14\,F(\phi),$$
$$\text{and} \quad F(\phi) = (\cos^{2/3}\phi + \sin^{2/3}\phi)^{-3/2}. \tag{2}$$

In (2), $H_0(\phi) = H_k\,F(\phi)$, and for $\phi = 0°$ and 180°, $m = 2$ and H_0 is just H_k. These relations incorporate the SW switching astroid and the Pfeiffer approximation [5].

Much of the analysis of conventional and heat-assisted magnetic recording, as well as the description of the thermal stability of recording media, can be addressed with this simple energy barrier picture. For example, the induced magnetization reversal process in magnetic recording, either at ambient or elevated temperature, can be understood as manipulation of the sign and magnitude of the ratio H_{eff}/H_k in equation (1). The numerator is increased in either process by elevating the applied H-field of the head, while in HAMR, one also diminishes the denominator $H_k(T)$ by heating the medium. As seen, this lowers and removes the energy barrier to facilitate M reversal. Furthermore, after recording and removal of the applied field, the particles of the medium reside in the demagnetizing field from surrounding bits, and for short recorded magnets, this field generally opposes the magnetization direction. Consequently, a recorded magnetic medium in storage is subject to internal fields which aid thermal decay by lowering the stability energy barrier.

To address the probabilistic process of thermally induced magnetization reversal (the same as fractional 'decay' of the composite magnetization of an ensemble of SW particles), we need to enhance the simple energy well picture by including the stochastic thermal energy of the particle (phonon–magnon interaction). In this view, the magnetic particle residing in the thermal bath of the medium must be considered to exhibit a mean thermal energy $\sim k_{\mathrm{B}}T$ while it resides in the energy well. Neél [6] and Brown [7] adapted standard Arrhenius thermal activation to this problem to arrive at an expression for the inverse of the statistical time constants for passage of the SW particle between the energy states of the two wells.

$$\tau_{\pm}^{-1}(T, H) = f_0 \exp(-E_B^{\pm}(H)/k_{\mathrm{B}}T). \tag{3}$$

Here, f_0 is an attempt frequency estimated by Brown to be of the order 10^9–10^{12} Hz. Gao and Bertram [8] have given an interesting approximate expression for the attempt frequency.

$$f_0 \cong 2\alpha\gamma H_k\sqrt{4\eta_0/\pi}\,\frac{[1 - (H_{\mathrm{d}}/H_k F(\phi))]^2}{F(\phi)^3}. \tag{4}$$

Here α and γ are the Gilbert damping coefficient and the electron gyromagnetic ratio, both of which appear in the Landau–Lifshitz equation to be discussed later. Weller [5] has given expressions for the probability of moment reversal based on (3), and an associated expression for the time evolution of the magnetization of an ensemble of particles. We show them here to provide a complete set for understanding thermal stability.

$$P(t, T, H) = \frac{\tau}{\tau_-} + \left(1 - \frac{\tau}{\tau_-}\right)\exp[-t/\tau(t, H)] \tag{5}$$

$$M(t, T, H) = M_0[2P(t, T, H) - 1], \tag{6}$$

where $\tau^{-1} = \tau_+^{-1} + \tau_-^{-1}$ and $M_0 = M(t = 0)$ is the initial magnetization after writing. Notice that for a typical case of an asymmetric double well, $E_B^- \gg E_B^+$ and so $\tau_- \gg \tau_+$, and so $\tau_+ \cong \tau$, in which case $P(t, T, H) \cong \exp[-t/\tau(t, H)]$.

From (3) and (2), we see that the argument of the exponential function governing the thermal decay rate from the metastable recorded state τ_+^{-1} is $\eta \equiv \eta_0(1 - H_{\mathrm{eff}}/H_k)^2$. By using (5) and (6), and by placing a requirement on the allowable fractional magnetization $m(t) = M(t)/M_0$ that must remain unreversed after lifetime $t = T$ for recorded media, one can place a requirement on the necessary value of η to achieve a target thermal stability. One important complication is that real recording media have a distribution of particle volumes in the ensemble, and the smallest volume particles are the least stable (that is, have the smallest value of η). A correct analysis would involve integration over a distribution of particle volumes, and this is illustrated in [5]. Nevertheless, we can give a simple illustration of how the parameters of the theory combine to yield estimates of the required η. This is done as a function of three parameters: $m(10) \equiv M(t = 10y)/M_0$, H_{eff}/H_k, and f_0. Figure 2 shows contour plots of η covering the space $0.9 \leqslant m(10) \leqslant 1$–$10^{-6}$, $0 \leqslant H_{\mathrm{eff}}/H_k \leqslant 0.4$, $10^{12} \leqslant f_0/\mathrm{Hz} \leqslant 10^9$. We observe that η must be higher to achieve $m(10) \to 1$ (very high stability), and to tolerate higher values of H_{eff}/H_k and f_0, as one would expect from the physical meaning of these parameters.

3. Magnetic configurations, areal density relations, and SNR

A primary metric for data storage capability for magnetic recording systems is areal density, or the count of digital bits per unit area of the recording surface. A surface density is an appropriate measure for magnetic recording since it has almost exclusively stored information in a single layer on or near the top surface of a recording medium. This situation can be contrasted with other forms of data storage, especially optical, where volumetric storage or three-dimensional storage has often been a goal. The difference arises principally because ‘projection’ and detection of magnetic fields is an extreme proximity effect, while light beams can be focused or propagated at a considerable ‘working distance’ from an optical transducer. Furthermore, light can often be transmitted through intervening layers of a storage medium without severe attenuation, so information can be detected at significant depths into the medium.

By carrying out a simple geometrical analysis of surface recording and accounting for the requirements for an adequate SNR, one can simply derive expressions for the AD that are useful for optimizing storage configurations and for projecting ultimate limits. This analysis is helpful in identifying the critical parameters requiring focus to maximize performance.

We first distinguish between the structural configuration of current thin film media and future ‘bit patterned’ media. For twenty years, the principal media in hard disk drives (HDDs) have been continuous metallic thin film structures deposited by sputtering. Compositionally, the material is usually a binary, ternary, or quaternary alloy system. Microstructurally, this material is composed of polycrystals, or grains. Normally, the aim is isolate the grains from one another magnetically, so that they form independent switching units. If they cluster magnetically to a strong degree, the media ‘magnetic granularity’ is too coarse, and the recording resolution is low and the noise high. Conversely, the best recording performance is achieved when there is a significant number ($\sim$a few hundred) of uniformly sized, magnetically

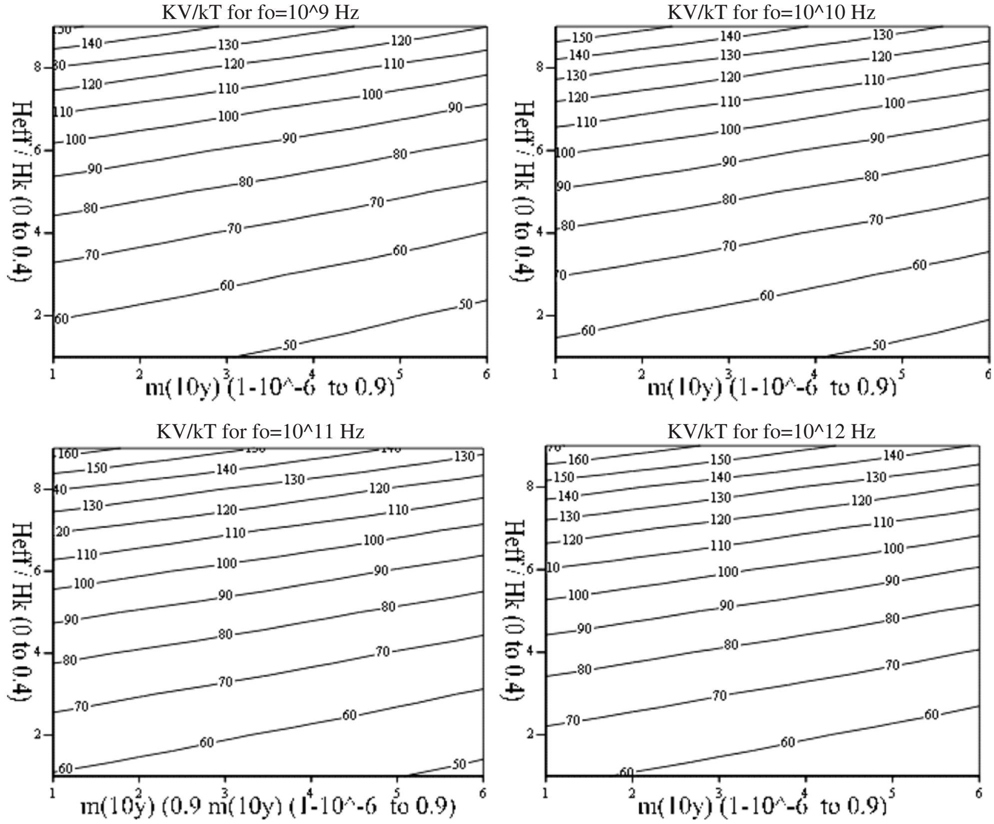

Figure 2. $\eta \equiv KV/k_BT$ as a function of $m(10) \equiv M(t = 10y)/M_0$, H_{eff}/H_k, and f_0. The horizontal axes show logarithmic intervals of $M(t = 10y)/M_0$ from 0.999 999 to 0.90, and the vertical axes number nine intervals of 0.05 for H_{eff}/H_k from 0 to 0.4.

decoupled grains per recorded zone (bit area). This approach of engineering a bit structure from a randomly grown ensemble of granular 'particles' depends on favourable statistics in a highly disordered system. The mass preparation of metallic film media with the desired set of recording attributes at low cost is a refined engineering art.

With the rapid pace of AD increase in HDDs and other recording technology, the pressure on scaling the geometry of the media structure has been relentless. This brings to the fore the difficult task of continuously scaling downward the mean grain size of a 'continuous' deposited film, while at the same time coping with the issue of long-term thermal stability of the grains. An alternate approach to media configuration is to envision the bits as isolated, preformed islands of nearly perfectly crystalline material. If the bit size is small enough that the island can be a single magnetic domain, this can be quite favourable for the magnetic stability of the induced moment, for the volume of the bit will still be quite large relative to the volume of the individual grains that would have to compose the bit in a continuous film structure. A large bit (particle) volume will have a favourable η even for a modest value of anisotropy energy density K, and thus the requirement on writing field strength is relaxed. Therefore, bit patterned media is an attractive configuration for future high density media structures.

However, accurate patterning of the islands is the new critical requirement that is traded for the reliance on 'good statistics' in continuous granular media. The principal measures of noise performance in recording media are the accuracy (high resolution, low shift) and repeatability (low 'jitter') of the placement of magnetization transitions which carry the encoded digital information. In bit patterned media, it is the pre-positioned boundaries of the magnetic islands that must be placed accurately. Whether this is done with lithographic processes [9] or chemical self-assembly [10], a completely new paradigm in media microstructure is opened. Consequently, the media SNR determinants are quite different, but low noise always comes back to low variance in the signalling to and from the medium.

Next we derive some very simple formulae for the AD based on geometric and thermal stability analysis. We are going to connect the grain volume appearing in the thermal stability criterion $\eta_0 \equiv KV/k_{\mathrm{B}}T$ with the recorded bit geometry in an HDD format. The surface area of a single bit is given by the simple product $A_{\mathrm{bit}} = \mathrm{TW} * L_{\mathrm{bit}}$, where TW is the track width and L_{bit} is the bit length. The film memory layer on a medium has a finite depth δ, and hence surface features have both area A and volume $V = A * \delta$. When recorded bits are composed of N polycrystalline grains, we can write $p * A_{\mathrm{bit}} = N * A_{\mathrm{grain}}$, where p is defined as the packing fraction, which is essentially the fractional area of the medium surface that is magnetic—particles are separated by non-magnetic material. Consequently, A_{grain} is the magnetic area of a grain, and thus excludes the non-magnetic boundary thickness. A final definition is $\mathrm{AD} \equiv A_{\mathrm{bit}}^{-1}$, which is the starting point of our simple derivation of the AD expression.

Manipulating the expressions in the above paragraph, we can easily arrive at the expression

$$\mathrm{AD} = \frac{p\delta K}{\eta N k_{\mathrm{B}} T}\left(1 - \frac{H_{\mathrm{eff}}}{H_k}\right)^2 = \frac{p\delta K}{\eta_0 N k_{\mathrm{B}} T}. \tag{7}$$

We stress that (7) is based entirely on a thermal stability criterion. Recall that earlier we noted that for granular media SNR $\propto N^M$, where $M = \frac{2}{3}$ to 1 and it is implied that $N \gg 1$. The formula (7) is instructive in that it tells us that the AD should scale in proportion to p, δ, and K, but inversely with η (or η_0) and $\mathrm{SNR}^{1/M}$. (SNR is explicit here *only* for granular media!) The scaling in proportion to δ is true to the extent that a magnetic particle is a single domain. However, as the particle aspect ratio δ/L_{bit} increases much beyond 2, the likelihood of formation of multiple domains in the grain increases, and (7) then breaks down. Perhaps more importantly, the proportionality between AD and K shows that increasing the storage temperature value of K is the logical path of HAMR for increasing the AD through the concurrent maintenance of thermal stability as the bit volume shrinks. We should also note that the apparent inverse relation of AD and $\mathrm{SNR}^{1/M}$ means that an operating storage system requiring a higher SNR will achieve a lower AD, and vice versa.

There is a second interpretation of (7) for bit patterned media. In that case, $N \rightarrow 1$, and the previous relation between the SNR and N does not apply. For bit patterned media, other parameters beside N govern the SNR, although the SNR is a critical requirement for satisfactory system operation. However, because N has moved to the minimum limit in (7), the AD has now become maximal (assuming that adequate SNR exists). Thus, we are led to the tentative conclusion that bit patterned media are an evolutionary path for maximizing the AD, at least from the thermal stability viewpoint.

4. Medium heating for high density thermomagnetic recording

In HAMR, the application of medium heating in a proper manner is the most critical step of the process. As we have seen, the reversal of the magnetic moment of a particle is accelerated by the heating of the material, whether the intent is writing or not. The decrease of $K(T)$ lowers the energy barrier against reversal, even when the material experiences no other magnetic fields than the self-field of demagnetization. This suggests that one should always limit the heat deposition for writing to an absolute minimum, and that the heat should be concentrated at the writing site, and not spread beyond. Furthermore, equations (3)–(6) show that reversal is an exponential rate-driven process, and so minimizing the time of heating minimizes the risk of unwanted switching or decay.

We have argued that HAMR medium heating and cooling needs to be rapid, and the heat application very localized. What are the length and timescales, and how much heat is needed? The recording density target (that is, the bit area) determines the length scale of the required heating. In fact, the dimension of recorded bits cross-track sets the requirement on the heating scale, since the down-track bit dimension might be determined by the output modulation of the heating transducer. Since $\mathrm{TW} * L_{\mathrm{bit}} = A_{\mathrm{bit}} = \mathrm{AD}^{-1}$ and $\mathrm{TW}/L_{\mathrm{bit}} \equiv \mathrm{BAR}$, we can express $\mathrm{TW} = [\mathrm{BAR}/\mathrm{AD}]^{1/2}$, where BAR is the bit aspect ratio. As an example, suppose we choose $\mathrm{BAR} = 4$ for $\mathrm{AD} = 1$ Tb in^{-2}. Then, we find TW $= 50.8$ nm. Evidently, the task in HAMR is to find a means of strong localized heating in the medium on a $\sim$50 nm scale. Clearly, it would be ideal if the imparted temperature profile were rectangular, as it would be uniform within the region of interest, with the sharpest possible edge gradient and minimum amount of excess heating or wasted power. Practical medium heating is likely to only approximate this, more or less.

The amount of thermal energy can be easily bounded by making a simple adiabatic heating estimate. The connection between heat absorbed and temperature rise is $Q = c_{\mathrm{v}} * V * \Delta T$, where c_{v} is the volume specific heat of the volume V of medium being heated, and that heat conduction out of the volume is at least momentarily negligible. The specific heat of typical metallic film materials in magnetic media is about 2.5 J cm^{-3} K^{-1}. The (minimum) volume of media heated is about $(50\ \mathrm{nm})^2 * \delta$, where $\delta \approx 20$ nm, and for the numerical estimate which follows, I boost this volume by a factor of ten to consider the immediate lateral heat spread beyond the thermal profile FWHM and into the depth of the disk. We can estimate the necessary temperature rise from the Curie temperature of a leading candidate medium for HAMR having high K. FePtX can be formulated to have $T_{\mathrm{C}} \sim 750$ K, and we will take the HDD ambient temperature to be 325 K. Then, from the above formula, we calculate Q to be about 5.3×10^{-13} J. The power associated with the deposition of this energy in a characteristic time for recording is an important parameter to know. From above, for $\mathrm{BAR} = 4$ and $\mathrm{AD} = 1$ Tb in^{-2}, we have $L_{\mathrm{bit}} = 12.7$ nm. The transit time of this bit under the recording transducer is L_{bit}/v, and for $v = 40$ m s^{-1}, $t_{\mathrm{trans}} = 0.318$ ns. Therefore, to deposit the heat Q in a fraction of the transit time, say about 0.1 ns, we anticipate a power requirement $P = Q/0.1\ \mathrm{ns} = 5.3$ mW. Although this is a very crude estimate, it shows the magnitude of power delivery needed for HAMR media heating.

What means of medium heating are possible? Thermomagnetic recording using optical heating of rotating disks has been practiced in commercial magneto-optical (MO) recording since the 1980s, so it would be a natural means to consider. The above estimate of media heating power is certainly in line with past and current practice in optical data storage drives utilizing laser diodes. A central issue for the high density recording of this paper would be development of a practical near-field (NF) irradiation technique with adequate spatial resolution and power transmission efficiency [11]. Alternatively, there have been references in the literature to localized heating of a recording medium by contact with a hot metal tip [12] and by proximate resistive heating [13].

Optical NF technology has been receiving increased attention recently. The quest has been to study devices which can transmit usable fractions of incident optical energy (near-IR, visible, near-UV) into the near field. The allows one to decouple from the limitations on spatial resolution of far-field diffraction where focused optical beam sizes would be given by $s \sim \lambda/\mathrm{NA}$; here NA is the focusing system numerical aperture $n * \sin\theta$, with θ being the half-angle of the converging focused beam in the medium of refractive index n. The design of

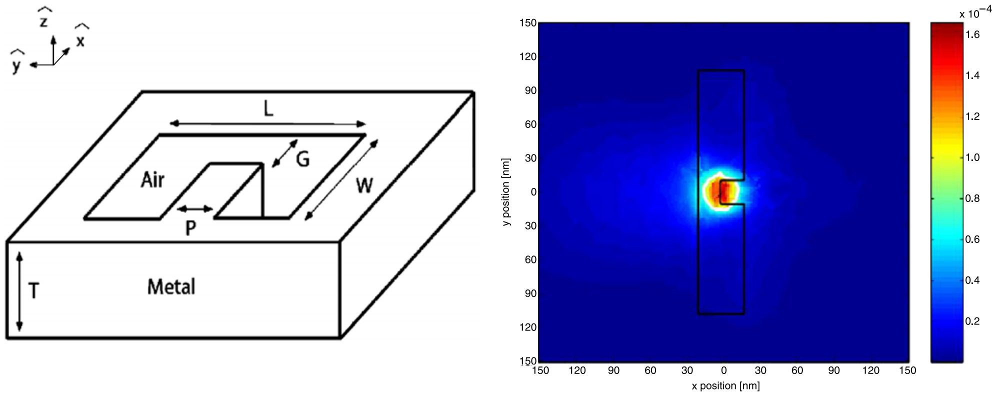

Figure 3. An example of near-field irradiance from a ridge waveguide (WG). A far-field focused beam irradiates the WG from above, and the emergent electromagnetic field below gap G has characteristic width of ~31 nm in the contour plot on the right. The geometrical parameters of the WG shown at the left have been optimized for efficient throughput.

NF transducers that provide *both* very high spatial resolution and transmittance of the order of 0.01 to perhaps 0.30 is non-trivial. Figure 3 shows an example of an optimized design for a ridge waveguide which produced a transmitted field of width 31 nm.

Optical heating is attractive as a non-contact means of heating the magnetic film. However, efficient light delivery to a flying head is a challenging optical design problem in itself. All such devices that have been discussed in the literature are conductive radiators (for example, apertures, antennae, waveguides), and the spatial extent and intensity of the radiated near-fields are governed by the size and shape of the transducer, as well as its proximity to the absorbing target. The alternative media heating methods indicated above may also present difficulties from a practical engineering viewpoint, such as waste heat generation in the transducer, physical contact with the medium, or media damage, either magnetic or tribological.

5. Data rate, readout, servoing, and the head–medium interface

In this section, we consider four practical functionalities of magnetic recording systems to see how HAMR measures up. The first is the rate of information transfer to and from the storage medium. The second is data readout or playback, which is complementary to HAMR, a writing process. The third function is active servoing of the mechanical system. The fourth function is maintenance of a robust, durable head–disk interface, which for an HAMR HDD system is a flying head on a rotating, rigid disk with a locally heated interface.

Writing and readout speed are important measures for the transfer of data to and from magnetic data storage devices. We need to consider how HAMR technology impacts and limits the data rate. Fundamentally, the raw data rate for transfer of information to and from the medium is related to the linear storage density and the transducer–medium relative speed, $R_{\mathrm{D}} = v/L_{\mathrm{bit}}$, which is essentially the inverse of the bit transit time given in the example in the previous section. For that example, using the future high AD value of 1 Tb in^{-2}, $R_{\mathrm{D}} = (0.318\ \mathrm{ns/bit})^{-1} = 3.14\ \mathrm{Gb\ s^{-1}}$. Since present-day HDDs feature R_{D} values approaching 1 Gb s^{-1}, we see that we need a feasibility assessment of HAMR technology for data rates in the range 1–10 Gb s^{-1} to provide for technology extendibility. Since HAMR is essentially a writing process, we focus here on issues that might limit the recording rate.

Two physical processes with characteristic rates appear to be central to HAMR. The first is heat flow, both into and away from the magnetic memory layer. Earlier, we quantified the rate for heating the medium, and it was based simply on the transit time of a recorded bit past the recording transducer. An important component of this argument is the issue of whether the heat source is temporally modulated or not. By far the simplest form of thermomagnetic recording uses a continuous (wave, or CW) heating source and a modulated magnetic field source, and we will restrict our consideration here to that mode. In this case, the warm up and cool down of a magnetic particle in the medium moving past the heating transducer is determined solely by the steady-state thermal profile (in the reference frame attached to the transducer) below the energy source. This profile is determined by the spatial profiles of energy absorption and heat conduction in the medium. The former is primarily a function of the energy output of the transducer and the coupling of that energy with the medium material. The latter depends entirely on the thermal design of the storage medium. Generally, as in optical recording, thermal energy deposited in a thin film stack atop a thick substrate will flow into the medium, and the characteristic transport time for the heat diffusion process in a homogeneous, continuum medium is $\tau = d^2/\kappa$, where d = diffusion distance, $\kappa = k/c_v$ (κ = diffusivity, k = thermal conductivity, c_v = volume specific heat). The three-dimensional heat flow is determined by the medium film stack geometry, and the thermal properties of the various materials in the medium. These effects can be accurately modelled with computer simulations. It is well known from the design of optical data storage media that lateral heat flow can be minimized with aggressive heat sinking of the medium memory layer; that is, by placing a relatively thick, highly thermally conductive film below the memory film. If the time of passage of a particle through the moving thermal profile does not significantly exceed the bit transit time, then the HAMR process should be robust, and the recording rate should be able to scale with the design data rate of the HDD. With this statement, we are imposing joint requirements on the transducer heating profile and the medium thermal design.

The second rate-limiting process in HAMR is the magnetization formation or reversal rate. This type of process is inherent in conventional magnetic recording too, although HAMR brings an interesting new element of elevated temperature to the magnetization dynamics. Gyromagnetic dynamics in ferromagnetic materials are reasonably well understood (via the Landau–Lifshitz (LL) equation), although the introduction of temperature dependent properties (equilibrium magnetization, crystalline anisotropy, damping coefficient) definitely adds to the complexity of the problem. If the medium temperature is elevated above the Curie temperature during writing, the local magnetization vanishes, and the rate and nature of the re-formation of the magnetization is critical for HAMR. The classical LL equation is not directly applicable to this situation, since the LL theory pertains to magnetic moments of constant magnitude in time and a system at 0 K. The LL equation has been adapted to elevated temperature [14], with the addition of a Langevin stochastic magnetic field to mimic thermal perturbation and/or with ad hoc addition of $M(T)$ and $K(T)$ to capture the equilibrium variation of these parameters, but application of the LL description very near T_C may be considered too extreme an extension of the theory. Nevertheless, some extensions of LL theory to HAMR have been undertaken [14, 15], and suggestions of magnetization formation at picosecond rates, seemingly exceeding LL limitations, have been seen experimentally [16]. At any rate, it is worth noting that a characteristic time from LL theory for electron moment dynamics would be the precession period in an applied field H, which is $\tau \sim (\gamma_e H)^{-1}$, where γ_e is the electron gyromagnetic ratio. For $H = 1$ T, $\tau \cong 5.7$ ps, although a realistic moment reversal time might be a few times τ, since damping is involved. Notice that reasonably strong applied fields are needed to keep the reversal timescale short. Even reversal times as long as 50 ps would not limit recording rates until ~20 Gb s^{-1} was reached. Clearly, we are assuming here that the reversal rate of the applied magnetic field from an inductive device is not a rate-limiting factor, although we should point out that this time dependence $H(t) \propto (V/R)[1 - \exp(Rt/L)]$

may be too slow if the driving voltage V is too small or if the LR response time L/R is too large.

Readout in HAMR is not thought to be substantially different from the same process in conventional recording, with the same issues presenting themselves. The challenge at ever increasing AD is that the volume of bit magnetization generating signals is shrinking, and so is the source energy for the read signal. This can only be compensated by elevating magnetization or improving the sensitivity of the read back transducer. Currently, magnetoresistive (MR) readout devices are well into their technological maturity, and a central question is whether their sensitivity (∼signal/power dissipation) can possibly be further increased by up to a few orders of magnitude. We assume appropriate geometric scaling of all dimensions in the read back problem, including the medium thickness and the head–disk separation. Both of these scaling parameters are problematic, since one tendency is to retain the memory layer thickness to maintain signal amplitude, while at some point the head will contact the medium and alter the wear mechanisms, since both surfaces have non-zero roughness. The bottom line in playback is the SNR, and increasing playback rates alone widens the bandwidth of the processing electronics, thus elevating electronic noise.

Alternative readout technologies, such as magneto-optic (MO) detection, particularly using near-field optics, should not be dismissed out of hand. Although quantum mechanical MO theory is reasonably well established, very little work has been done on the practically realizable response to electromagnetic near fields. Or some signal amplification scheme such as MAMMOS [18], as is used in MO recording, might be useful for implementing MO readout.

Electronic signalling techniques from communications theory have been important historically in magnetic recording. One such concept is digital multi-level recording. To date, digital magnetic recording has relied on binary, or two-level, signalling. However, development work from optical data storage and other communications fields have explored M-ary level signalling channels (M is the number of signal levels) [19]. Such approaches do require additional SNR, but they can deliver good payoff in effective areal density, offering more information per recorded feature site on the medium.

Servoing is a central mechanical function in recording systems, particularly HDDs. Closed loop control systems are employed to hold the recording transducer on the data track during writing and reading, and they also are involved in the rapid seeking and settling of the transducer when the system requests access to recorded information or a location for writing. As the physical dimensions of recorded bits continues to shrink, with or without HAMR, the demand on the mechanical servo system to find and follow data in the face of higher media speeds and external vibrations escalates.

Finally, we earlier touched on the head–disk interface problem in future ultra-high density recording. Because HAMR intentionally heats the interface on a small spatial scale by several hundred kelvins for upwards of 10^7 cycles, it clearly adds stress to the usual tribological materials system. This subject has been addressed in recent papers and presentations [17]. Clearly, it will be advantageous to choose the HAMR recording medium and heating scheme to minimize the maximum temperature of the thermal cycling. And although it is not a mechanical issue, extensive thermal cycling of the magnetic medium could produce subtle changes in the material's magnetic properties, which potentially could impact the SNR over the lifetime of the recording device.

6. Theoretical and modelling tools for HAMR assessment

We offer here a brief summary of some of the important analytical tools for evaluating the magnetic recording physics of modern systems. Our particular focus is on HAMR in HDD systems, although many of the techniques and tools are general and widely applicable to other magnetic or optical recording systems. Several of these have been referenced earlier in this review, and more detail will be provided here. The general problem that we must address in the recording physics of HAMR writing is to provide a description of $M(\vec{r}, t, T)$ under the action of $T(\vec{r}, t)$ and $H(\vec{r}, t)$.

A first fundamental theory is the magnetic switching of particles as described in the Stoner–Wohlfarth (SW) model [5], combined with the statistical description of the switching and relaxation of such particles in time under the action of temperature and applied field from Arrhenius–Neél–Brown (ANB) [6, 7]. This was discussed earlier in section 2. The dynamical equation of single magnetic moment particles is provided by the Landau–Lifshitz (LL) equation, shown in the next paragraph. With these basic theoretical ingredients, rather complex numerical micromagnetics simulations are built up [20]. Our intent here is not to review micromagnetics theory [21], but we do want to address two specific extensions of these combined theories that are very useful in modelling magnetic recording media.

Brown's paper [7] describes the role of a stochastic 'thermal field' which can be added to the effective field of equation (1) to produce a Langevin form of the LL equation. The ith vector component of the thermal field is a mean zero field with a standard deviation value of

$$H_{\mathrm{th},i} = \sqrt{\frac{2k_{\mathrm{B}}T\alpha}{VM_{\mathrm{s}}\gamma(1+\alpha^2)\Delta t}} \tag{8}$$

where V is the particle volume and Δt is the LL equation integration time step. The LL equation is

$$\frac{\mathrm{d}\vec{M}}{\mathrm{d}t} = -\gamma(\vec{M} \times \vec{H}) - \frac{\alpha\gamma}{M}[\vec{M} \times (\vec{M} \times \vec{H})] \tag{9}$$

with the first term on the right-hand side (rhs) representing magnetic moment precession, the second term on the rhs describing damping of the moment motion. Very often the second term on the rhs is replaced with the physically more justifiable Gilbert damping term $+\frac{\alpha}{M}(\vec{M} \times \frac{\mathrm{d}\vec{M}}{\mathrm{d}t})$ to create the LLG equation. The differential equation (9) or the LLG equation with (8) included in the (effective) H-field can be solved for an ensemble of interacting SW particles to provide a deterministic solution for a many-body problem. Alternatively, the ANB processes reflected in (6) can be estimated by applying a Monte Carlo process via the Metropolis algorithm [22] to an ensemble of SW particles to arrive at the quasi-equilibrium states $M(t, T, H)$ for the ensemble.

For writing in HAMR, a theory incorporating SW and ANB behaviour during cooling in a field would be useful. Field-cooled magnetization (FCM) and thermoremanent magnetization (TRM) [6, 23] are such processes that can be adapted to HAMR [24]. As discussed earlier, the LL or LLG equation can also be applied to HAMR. However, in either case, as the medium temperature approaches the Curie temperature T_{C}, a critical point for the cooperatively magnetized ferromagnet, the assumptions underlying the supporting models or theories (SW, ANB, LL) become highly questionable. Therefore, more sophisticated approaches for temperatures near and above T_{C} are required. In this situation, one may need to employ first principles atomistic computations incorporating quantum mechanics [25].

A somewhat simpler approach has adapted the LLG equation with a variable $|\vec{M}|$ and for temperatures below or above T_{C} [15]. Figure 4 shows an example of the dynamic reversal of the component of particle magnetization along the applied field direction when the temperature was momentarily elevated above T_{C}, as might be done in an HAMR process. The reduction of the particle equilibrium $M_{\mathrm{s}}(T)$ with rising temperature is accounted for in this model. In this example, the medium H_k at $T = 300$ K is 50 kOe, and the applied reversal field is only 2 kOe. The Gilbert damping coefficient is 0.1, and the average demagnetization field for

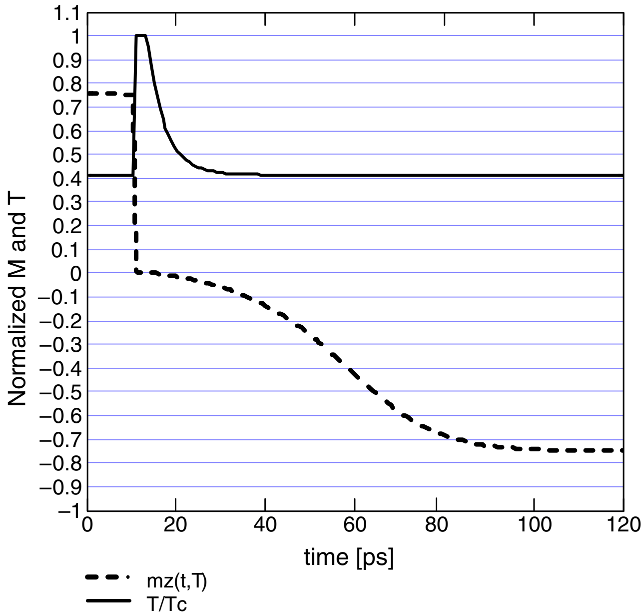

Figure 4. An example of rapid particle magnetization reduction and reversal as predicted by an adapted LLG equation following extremely rapid heating and cooling of the particle, as with a fast laser pulse. Normalized magnetization (dotted curve) along the applied and anisotropy field direction $m_z = M_z/M_{z,0\ \mathrm{K}}$ and normalized particle temperature (solid curve) are shown. See the text for further details.

the $M(T = 0\ \mathrm{K}) = 800$ emu cm^{-3} medium is included in the calculation. The heating is extremely brief, with the value $T_{\max} = 775$ K (relative to $T_\mathrm{C} = 773$ K) quickly reached at $t = 10$ ps and lasting just 2 ps before it drops exponentially back to ambient temperature with a 4 ps characteristic fall time. The reversal characteristic is extremely sensitive to both the damping coefficient (reversal is more likely with higher damping) and the temperature–time profile $T(t)$. We notice in figure 4 that the magnitude of the normalized magnetization is about $0.76 * M_{\mathrm{s},0\ \mathrm{K}}$ at the ambient temperature 320 K before and after the switching event, which completes in about 100 ps.

A final example of HAMR modelling features a detailed micromagnetics simulation that incorporates solution of LLG dynamics for an ensemble of interacting magnetic grains with anisotropy perpendicular to the memory film plane. Figure 5 shows the distribution of grain sizes in the modelled medium, the imposed moving thermal profile, the time modulation of a uniform applied magnetic field, and the final recorded pattern. The applied field of 3 kOe is too weak to record this 10.8 kOe H_k medium without the thermal assist. With the peak heating about 100 K above the Curie temperature of the modelled medium, the HAMR writing is very effective. A model of this type is useful to complement experimental work for the design of HAMR systems.

7. Estimate of the ultimate limit of areal density

In section 3 we derived an expression (7) for the areal density of surface magnetic recording based on a thermal stability argument. In this section we will use that relation to make an estimate of the ultimate limit for the AD in magnetic recording. We earlier observed in

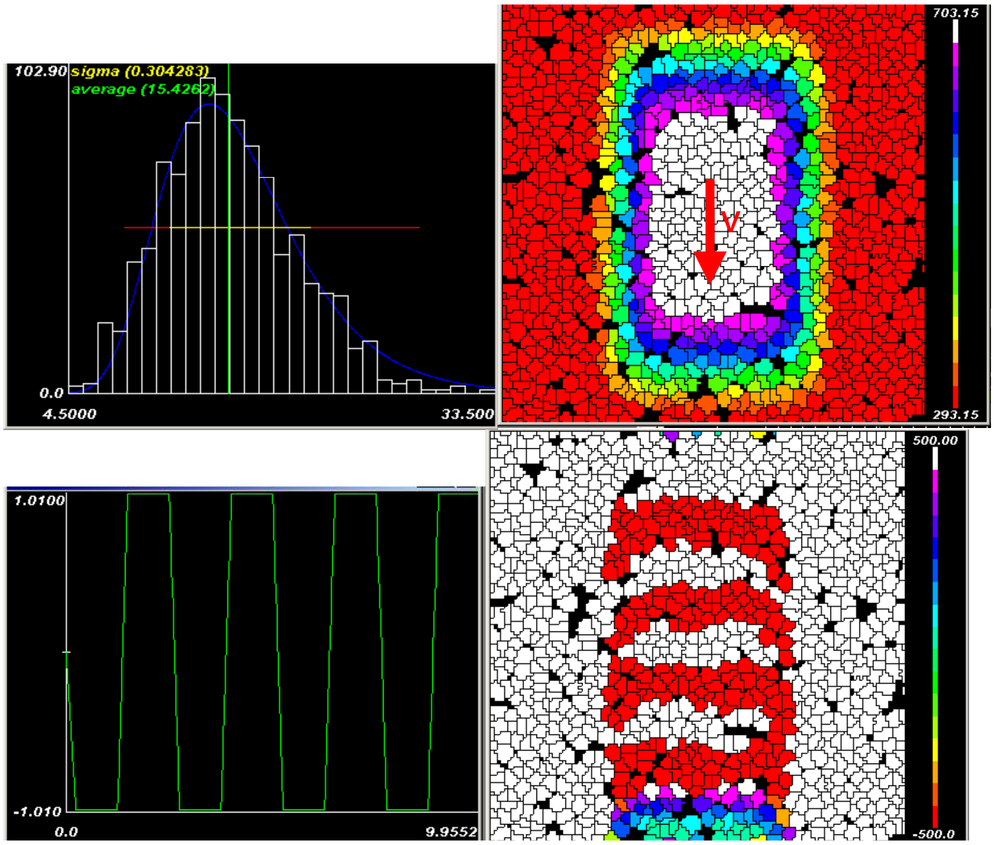

Figure 5. (a) Through (d), left to right, top to bottom; (a) lognormal distribution of grain sizes in the model, with $\langle d_g \rangle \sim 10$ nm; at $T = 293$ K the medium H_k is 10.8 kOe and $M_s = 500$ emu cm^{-3}; (b) a contour plot of the imposed super-Gaussian thermal profile on the medium, which moves from top to bottom at 25 m s^{-1}; the spot size is about 150 nm by 250 nm, and the peak temperature is about 703 K, relative to a Curie temperature of 600 K; (c) the normalized time-modulated, uniform applied magnetic field over 10 ns; peak field strength is 3 kOe; (d) the recorded pattern of crescent-shaped marks, with $-M_z$ imposed on a dc-erased background of $+M_z$; the thermal profile is just departing the viewing window.

section 3 that patterned bit media with a single magnetic domain per bit island was the path forward with the most leverage for AD advantage since $N \rightarrow 1$ in the denominator of the formula. In fact, this provides a factor of ~30–300 improvement, since granular bits tend to have N in this range to achieve usable SNR. Once again, we must stress that taking N to unity does *not* mean that a minimum level of the SNR can be abandoned—it simply indicates that medium SNR must be achieved through control of signal or bit variance by means other than through the statistics of counting over a distribution of small grain sizes.

We must point out that the estimation that follows ignores the possibility that unanticipated engineering difficulties in the recording system could arise to make our estimate unachievable. Such an eventuality is impossible to predict, and we simply ignore that issue in making a purely physical estimate of an ultimate limit. What follows should be interpreted in this context.

Assuming that an adequate level of SNR can be acquired with bit pattern media, the single domain bits with a relatively large volume per magnetic particle deliver the path of maximum thermal stability. Now we must set reasonable levels for the other parameters in (7)

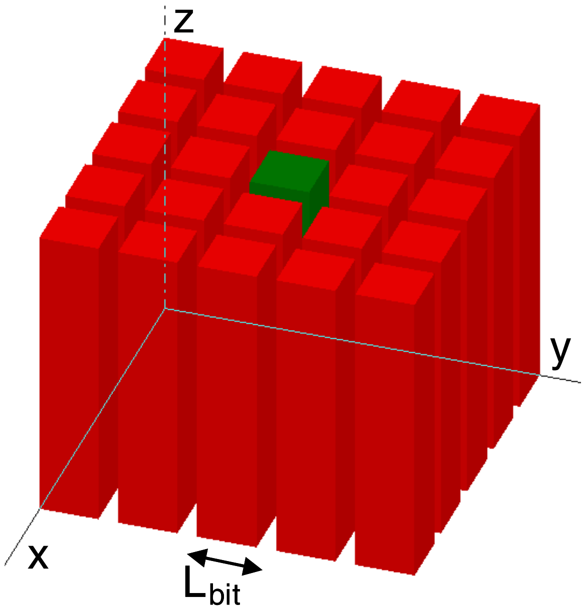

Figure 6. A schematic representation of a regular array of patterned, single domain magnetic cells with remanent magnetization along the z-direction. This is the idealized configuration used for the estimate of the ultimate areal density achievable with HAMR, based on thermal stability arguments.

to make our estimate. In figure 6, the pattern architecture shown has a packing fraction p of 0.56, which follows for a choice of square footprint bits with an $L_{\text{magnet}}/L_{\text{bit}}$ ratio of 0.75 or 3:4. While this appears reasonable, and it might possibly be increased with optimization, it is difficult to imagine p exceeding 0.8 or so. The medium's thickness δ will be taken to be 10 nm initially. Later, one should examine the aspect ratio δ/L_{magnet} for the prismatic bits to assure that single domain formation with HAMR writing (for example, a thermal gradient might exist through the depth of the medium) is likely. The anisotropy energy density K will be taken as 7×10^7 erg cm^{-3}, which is an estimated maximum for the FePtX alloy system. We set η_0 to 60, which seems reasonable, and finally T is set to 330 K, an estimated ambient temperature for an HDD. This parameter set gives about 92 Tb in^{-2}, roughly 10^3 times the product AD value at the time of this writing. One might easily imagine this number varying by $\pm$50% through some variation in the parameters we have selected, but it does establish a range for our estimate of a physical limit.

What does this mean dimensionally? The limiting AD cited above corresponds to $L_{\text{bit}} = 2.64$ nm for the square footprint bits, which is roughly 10–12 atoms along a bit edge. Consequently, the cross-section of the bit in the medium plane corresponds to $\sim$60–80 atoms, while the volume of the magnetic bit contains about $8 \times 8 \times 50 = 3200$ to $9 \times 9 \times 50 = 4050$ atoms. So we see that we are well above the limit of 'single atom' storage. However, when recording bits serially along a track, as in an HDD, the allowable upper limit of variation in the bit transition position along the track is usually taken to be $\sim 0.1 * L_{\text{bit}}$, which gives a medium SNR $\sim 20 \log\ (\text{signal}/\sigma_{\text{sig}}) = 20 \log 10 = 20$ dB. Notice that this variation would definitely be at the single atom level along the track direction.

What particle aspect ratio resulted in the above calculation? We have $\delta/L_{\text{magnet}} = 10\ \text{nm}/(0.75 * 2.64\ \text{nm}) = 5.05$. This may be too large for the tall, narrow prismatic particle to remain a single magnetic domain. We can parameterize the particle aspect ratio and modify our algebraic expressions. Define $A = \delta/L_{\text{magnet}}$ where A is the particle aspect ratio. Since $L_{\text{magnet}} = L_{\text{bit}}\sqrt{p}$ and $L_{\text{bit}}\sqrt{p}$ and $L_{\text{bit}}^2 = A_{\text{bit}} = \text{AD}^{-1}$, we can derive a new expression for

δ: $\delta = A\sqrt{p}\,\mathrm{AD}^{-1/2}$. If we substitute this expression for δ into (7), and re-express the result for AD, we find

$$\mathrm{AD} = p\left[\frac{AK}{\eta_0 k_B T}\right]^{2/3}. \qquad (10)$$

Let us use (10) with the same values of η_0, K, and T used before, except we will set $A = 3$ (safer for single domain stability) and $p = 0.8$ (compared to 0.56 before). Equation (10) then yields 93 Tb in^{-2}, a value very close to the earlier estimate. However, the value of δ for this parameter set is 7.06 nm. In this example, we have recovered nearly the same value of AD, even though δ was reduced, by boosting p by about the inverse of the δ reduction factor. This exercise illustrates that the value of AD $\sim$ 90 Tb in^{-2} is robust with respect to particle aspect ratio adjustment by increasing the particle packing fraction.

We note that for the medium material selected (FePtX), the room temperature value of H_k is roughly 100 kOe, far beyond the range of writability for heads with an anticipated output flux density limit of about 25 kG. Therefore, we are far into the realm of HAMR in this estimate. It is worth noting that the potential material system SmCo could have a K (and hence H_k) value about three times higher than FePtX, and this might push our AD estimate into the 250–300 Tb in^{-2} range.

8. Conclusion

We have considered the question of the ultimate areal density in magnetic recording that is physically realizable, solely on the basis of thermal stability of single domain ferromagnetic particles. Ignoring a myriad of possible engineering difficulties in the recording system, and supposing that we use media made with materials with the highest known values of magnetocrystalline anisotropy, we arrived at an estimated range of AD values of $\sim$50–300 Tb in^{-2}. This recording utilized a bit pattern media configuration, and it definitely required the HAMR process for writing. A value of $\sim$100 Tb in^{-2} is about 10^3 times greater than that delivered by today's commercial HDD products.

From the simple AD expressions derived, we found that the greatest leverage for advancing toward the ultimate physical limitations of stable magnetic recording comes from (a) elevating the storage medium magnetocrystalline anisotropy K, and (b) storing a single bit in one single domain magnetic particle.

Areal densities in the range cited can be placed in context by realizing that, at 50 Tb in^{-2}, the entire printed contents of the United States Library of Congress ($\sim$10 TB) could be stored on a 30 mm diameter disk. This is about the size of a US fifty-cent coin.

When might one expect this ultra-high AD to be achieved? This too is impossible to predict, but it is interesting to apply the type of Moore's Law exponential growth seen in figure 1 to make projections. The exponential growth law is $\mathrm{AD}/\mathrm{AD}_0 = (1 + 0.01\, r[pc])^{t[y]}$, where r = compound annual growth rate in per cent, and t = time of growth in years. If we take the areal density growth factor on the left-hand side to be 10^3, we find the time projections for various rates in the following table.

CAGR (%)	Time (years)
20	37.9
30	26.3
60	14.7
100	10

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