MAGNETIC MEDIA, MAGNETIZATION REVERSAL

This article describes the magnetization reversal (magnetization switching) processes and the time-dependent reversal phenomena that occur when data are stored in magnetic recording media. These reversal processes determine the response of the medium to the applied magnetic field during the writing of data and the stability of written data patterns over the lifetime of the medium. Because magnetization reversal at low fields is a thermally activated process, the time scale over which the writing field is applied affects the switching field or coercivity of the medium, and thus the field that the write head needs to apply in order to write the data. Additionally, time-dependent magnetization reversal can lead to "superparamagnetic" behavior in which the written patterns are

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thermally unstable and read-back signals decay with time. These considerations apply to all magnetic media, but are most prominent in hard-disk media, and most of the examples described in this article refer to hard-disk media. Superparamagnetic and time-dependent effects are becoming increasingly important with the continuing increase in storage density and data rates in recording systems and are expected to limit the ultimate storage density achievable in hard-disk media.

MECHANISM OF MAGNETIZATION REVERSAL IN MAGNETIC MEDIA

Information is written onto hard-disk magnetic recording media when a magnetic write head passes near the surface of the recording medium. The head is magnetized by a varying current whose polarity changes according to a digitized stream of data. The resulting head field saturates the medium to form domains of opposing magnetization directions. The precise location and definition of these magnetization transitions is of great importance for the achievable linear density of data. Any fluctuation in the mean position of the transitions introduces noise, while the definition of the lateral bit boundaries limits the achievable track density.

The switching mechanism of the recording medium, that is, the reversible and irreversible processes that occur as the magnetization changes in response to an applied field, determines the recording performance of the system. The switching behavior depends upon the structure of the medium—whether, for instance, it is made from a continuous thin film with in-plane magnetization directions (as in a hard disk), perpendicular magnetization (as in perpendicular hard-disk media or magneto-optical media), or from magnetic particles embedded in a matrix (as in flexible media). In continuous thin-film media, the deposition conditions are usually chosen to produce a film consisting of small magnetic grains separated by nonmagnetic grain boundaries. Therefore both thin-film and particulate media may be treated as assemblies of small, single-domain particles subject to magnetic interactions. The switching mechanism of the medium depends on the switching behavior of the individual particles and also, importantly, on interactions between the particles via magnetostatic (long-range) or exchange (short-range) forces.

The switching mechanism of an isolated single-domain particle depends on the particle anisotropy, size, and magnetization. The simplest description of magnetization reversal is that the magnetization vector rotates uniformly (coherently) as the external field is varied. This coherent rotation model was described by Stoner and Wohlfarth (1) and was extended (2,3) to include thermally activated switching over a single energy barrier. However, magnetic particles often show incoherent switching in which the magnetization within the particle is not uniform (4), and the energy barrier may be complex. Recent magnetic force microscopy (MFM) investigations of magnetization reversal have helped elucidate the behavior of isolated magnetic particles (5), which is necessary for understanding of the switching behavior of assemblies of interacting particles.

Even if the switching behavior of individual particles is understood, the interactions between particles leads to complex collective behavior of the medium. For example, if the data track is initially prepared in a dc-erased state, so that the magnetization direction is uniform and parallel to the data track, new data will be written onto the track either in or against the initial magnetization direction. These are known as "easy" or "hard" transitions, respectively, and their physical location with respect to the recording head differs because of the superposition of the field from the previously erased track and the field from the head. Similarly, the effect of preexisting magnetization patterns leads to nonlinear bit shift in newly recorded data (6). It can therefore be difficult to calculate the magnetic response of a recording medium.

The behavior of magnetic media has been investigated using micromagnetic calculations by treating the medium as an assembly of interacting Stoner–Wohlfarth single-domain particles (7–9). This assumption has been shown to be valid for grains with sizes comparable to the magnetic exchange length or smaller (10), which is the case for thin-film media. For pure cobalt and permalloy (NiFe) the exchange length is 7 nm and 20 nm, respectively. The reversal dynamics can then appropriately be described by solving coupled Landau-Lifshitz equations (11). It has been shown that the solutions of this nonlinear system of ordinary differential equations have a rich structure that captures the collective magnetization processes. The magnetization direction of adjacent grains is found to be correlated, and the size of these correlated regions governs the noise properties of the medium. Exchange interactions enlarge magnetic correlations and therefore increase noise and large-scale percolation structures, in which the jaggedness of the bit boundary is large compared to the bit width (12). As an example, Fig. 1 (13) shows how the presence of exchange coupling between grains affects the magnetization patterns at a written transition. Theory has also shown that magnetostatic interactions lead to the development of magnetization vortices in which the magnetization locally follows a circular pattern. These vortices have been imaged experimentally (14).

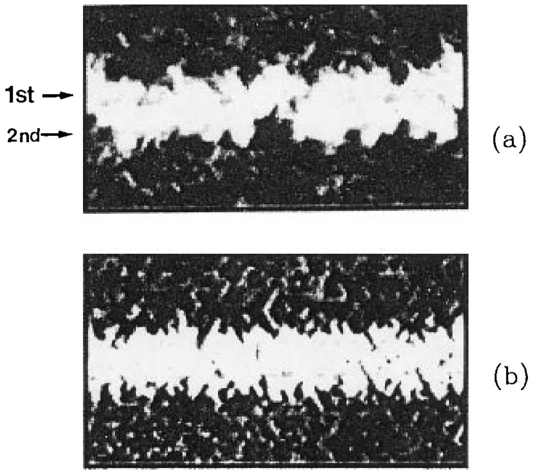

Figure 1. Micromagnetic simulation of two transitions (bits) written into a hard disk, (a) with and (b) without exchange coupling. The track direction is top to bottom. The gray scale represents the magnetization direction in the film plane parallel to the track direction, with white parallel and black antiparallel (13). Reprinted with permission of the authors and the Institute of Electrical and Electronic Engineers.

Application of this modeling has yielded a detailed understanding of the magnetization processes occurring during the writing process. However, with the need for high-frequency writing and with the continued decrease of grain size it is apparent that the deterministic Landau–Lifshitz time evolution now needs to be augmented by more sophisticated dynamical models that also take into account thermal fluctuations (15).

TIME DEPENDENCE OF MAGNETIZATION PROCESS

There has been considerable study of time-dependent magnetic phenomena (16–19,19a). Recently, changes in coercivity with field sweep rate have become important in the design of high-density recording media (20–32). Analysis of time-dependent phenomena treats magnetic media as consisting of an assembly of single-domain particles having magnetic anisotropy energy K and switching volume V. K represents the tendency of magnetization to lie along an "easy axis," and V is the volume of the particle that needs to switch its magnetization to initiate reversal of the magnetization direction in the particle. K includes contributions from magnetocrystalline anisotropy K_u as well as from the shape anisotropy of the particle and any magnetostrictive effects. V is equal to the physical particle size if the magnetization rotates coherently during reversal. V may be smaller than the physical particle volume if switching is incoherent, or may exceed the particle volume if interactions cause particles to switch cooperatively. The ease of switching the magnetization depends on the energy KV needed to rotate the magnetization so that it is perpendicular to the easy axis. The susceptibility of media to thermal effects (i.e., spontaneous reversal of the magnetization) therefore increases as the parameter KV/kT decreases, where k is Boltzmann's constant and T the temperature. KV is measured either from the sweep-rate dependence of coercivity or from the time dependence of magnetization in an applied reverse field.

Switching volumes can be measured from the time dependence of magnetization $M(t)$ in an initially saturated sample placed in a reverse magnetic field H_{rev} (16,18,35,36). The magnetization often follows a logarithmic relation such that

$$M_{\mathrm{r}}(t, H_{\mathrm{rev}}) = M_0(t, H_{\mathrm{rev}}) + S(H_{\mathrm{rev}})\ln(t) \tag{1}$$

where M_0 is the initial remanent magnetization and $M_r(t)$ is the remanent magnetization at time t at H_{rev}, and S is the magnetic viscosity. The functional form of this relation results from a superposition of exponential decays for different populations of magnetic particles. Figure 2 shows a linear dependence of magnetization on ln(t) (24). The activation volume V^* is then related to S by

$$V^*(H) = \chi_{\mathrm{irr}} kT/M_{\mathrm{s}}S(H) = kT/M_{\mathrm{s}}H_{\mathrm{f}} \tag{2}$$

where χ_{irr} is the irreversible susceptibility. This is the rate of change of irreversible magnetization with applied field that can be found by differentiation of the remanence curve for the material, measured using a vibrating sample magnetometer (VSM) or alternating gradient force magnetometer (AGFM). H_f is known as the fluctuation field, a fictitious field whose effect on the magnetization is equal to the effect of thermal fluctuations.

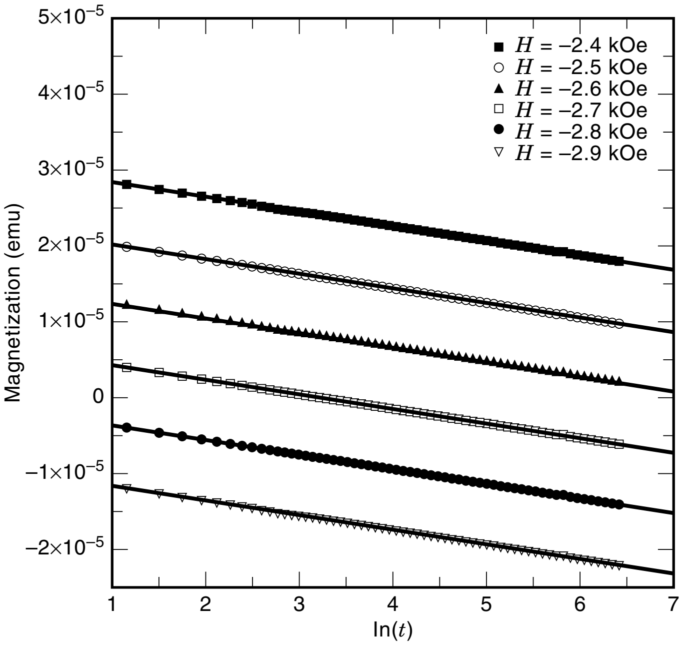

Figure 2. Decay of magnetization with time t for a Fe/Pt multilayer sample initially saturated at 10 kOe, then held in a reverse field of between 2.4 kOe and 2.9 kOe (24). Reprinted with permission of the authors and the American Institute of Physics.

The logarithmic relation is followed for systems that have a wide distribution of energy barriers for reversal of the magnetic particles (19a). A narrow distribution of barrier heights leads to a nonlinear dependence on ln(t) but the switching volume can still be calculated from a series of time-dependent curves separated by small increments in applied field (27). These measurements are commonly done in an AGFM. It should be noted that V^* has a different physical interpretation from V defined in Eq. (4), below, since V^* has an explicit field dependence. V can be identified with $V^*(H_c)$ (20).

Switching volumes determined using this method have been reported for a range of materials, including barium ferrites (37), iron oxides (38), α-iron particles (38,39), and CoCrTa (27) and CoCrPt (41) hard-disk media. This analysis can also be applied to continuous magnetic films which switch by domain-wall motion, for instance rare-earth/transition metal amorphous films used in magneto-optical media (40,40a,40b,40c). In this case, V^* represents the volume of part of a domain wall pinned at a pinning center.

Thermally activated switching leads to a time-dependent coercivity. The variation of coercivity with the scan rate of the external applied field is commonly analyzed using a method described by Sharrock (20). This assumes an assembly of noninteracting single-domain particles whose magnetic switching is thermally assisted. The particles have uniaxial magnetic anisotropy of magnitude K and saturation magnetization M_s. The coercivity H_c is given by

$$H_{\mathrm{c}}(t) = H_0\{1 - [(kT/KV)\ln(At)]^n\} \tag{3}$$

where half of the particles reverse their magnetization in time t when the applied field is $H_c(t)$. A is a constant related to the attempt frequency of switching, of the order of 10^9 s^{-1}. The geometrical factor n takes a value between 0.5 and 0.7

(1,33) depending on the angle between the easy axis of the particles and the applied field. H_0 is given by $2xK/M_s$, where x is a geometrical constant related to n and has a value between 0.5 and 1. K can be found from H_0 or from other measurements such as torque magnetometry.

The model was developed originally for particulate media such as iron oxide or ferrite particles, but has more recently (24,26,28,30) been applied to thin-film media, for which the assumption of noninteracting particles is even less justifiable. However, Monte Carlo simulations of switching in thin-film media (15,23,34) indicate that an equation of the form of Eq. (3) still describes the variation of measured coercivity with sweep rate, but with a higher exponent of $n = 1$ (23) or $n = 0.735$ (15) due to interactions between the magnetic grains. An exponent of $n = 1$ reduces Eq. (3) to the form

$$H_c(t) = C + (kT/M_s V)\ln(t') \tag{4}$$

which is linear in $\ln(t')$, where t' is the rate of change of the field and C is a constant. This linear form has also been used to analyze time dependence of coercivity in media (24). It may be difficult to distinguish between Eq. (3) and Eq. (4) unless the coercivity measurements cover several decades of scan time. Using Eq. (3) or (4), V can be found from the scan-rate dependence of H_c using an AGFM or a Kerr-effect looper that measures the hysteresis loop of the sample. Comparison between V and the physical particle size (determined by microscopy) yields information about the switching mechanism and magnetic interactions between particles.

Until recently, there had been relatively little application of this analysis to thin films, partly because its validity has not been well established for interacting systems. Figure 3 shows an application of Eq. (3) to data from a CoCrTa/Cr hard disk (30). There are many other examples in the literature. For instance, in the case of noninteracting, aligned particles of ferrite particulate media with $n = 0.5$, the switching volume was found to be smaller than the physical volume, implying incoherent rotation of the magnetization (25). Analysis using an exponent of $n = 1$ in CoCrTaPt media (26) and in Fe/Pt multilayers (24) showed switching volumes smaller than the grain volume. However, in CoSm deposited on a Cr underlayer (29), the switching volume was similar to the Cr grain size and considerably larger than the CoSm crystal size, and in CoCrPt/Cr the switching volume was also found to be considerably larger than grain size (27). A comparison of V with $V^*(H_c)$ in Fe/Pt multilayers showed reasonable agreement (24).

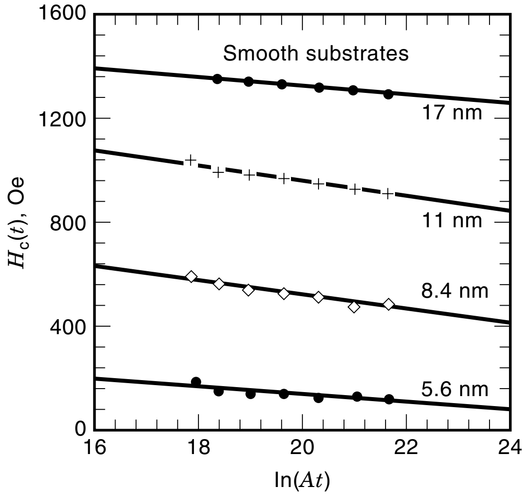

Figure 3. The dependence of coercivity H_c on the rate of change of the magnetic field for CoCrTa hard-disk media. The field scan rate is proportional to $1/t$, and A is a constant. As the field scan rate increases, the measured coercivity increases. Data are shown for four different thicknesses of CoCrTa films (30). Reprinted with permission of the authors and the Institute of Electrical and Electronic Engineers.

LONG-TERM STABILITY OF MAGNETIZATION PATTERNS

The stability of written magnetization patterns is related to the time-dependent magnetic effects and magnetic viscosity described above. If the product KV/kT in the media is sufficiently small, spontaneous magnetic switching of the particles can occur and the amplitude of the read-back signal decays. This phenomenon is of practical concern if there is significant decay of the signal during the lifetime of the media.

Long-term stability and time-dependent coercivity of media have been estimated by performing Monte Carlo simulations of the behavior of arrays of magnetic grains (15,23,34). These simulations show the difference between the effective coercivity of the medium for long-term data storage, relevant to signal readback, compared to the effective coercivity during writing, where the applied field varies at high frequencies. Using parameters suitable for 10 Gbit/in.^{2} longitudinal recording, the reading and writing coercivities differ significantly if KV/kT is less than about 100. The decay of written bits in longitudinal media was shown to depend strongly on KV/kT, on the recording density, and to a lesser extent on the grain aspect ratio and on interactions between grains given by M_s/H_k. H_k is the anisotropy field, which is the field needed to rotate the magnetization away from the easy axis. Choosing the stability criterion that the magnetization midway between two transitions at 400 kfci (400 thousand flux changes per inch) must exceed 0.4 memu/cm^2 after 6 months, the suitability of various values of K and M_s can be plotted on a map, Fig. 4 (15), based on a grain size of 10 nm. Only region 5 is suitable for stable recording; in region 1 M_s (and the signal) is too small, in region 2 transitions overlap, magnetostatically reducing the signal, in region 3 the signal decays thermally, and in region 4 the head field cannot saturate the medium. For the 10 Gbit/in.^{2} example cited, optimum signal was obtained for reading coercivities of about 3500 Oe and writing coercivities of about 5000 Oe.

Thermally assisted switching of the magnetic domains occurs rapidly at head-on transitions in longitudinal media because there are strong demagnetizing fields tending to promote magnetization reversal. In perpendicular media, the demagnetizing fields at the transition are less strong and the media are believed to have better thermal stability. Stability is also enhanced by the greater film thickness (and grain volume) in perpendicular media (42). In longitudinal media, simulations show that signal loss is likely to be significant for values of KV/kT less than about 60. This is not an issue for existing media, which have ratios of order 2000, but as grain sizes and film thicknesses continue to decrease, signal decay will become an increasing problem.

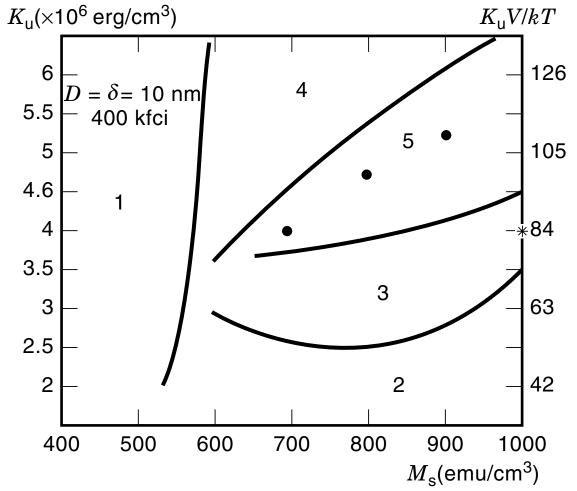

Figure 4. Calculated regimes of different behavior for a hard disk medium with 10 nm grain size D, 10 nm film thickness δ, and a range of values of magnetocrystalline anisotropy K_u and saturation magnetization M_s. The bullets indicate the maximum readback signal for different M_s values. In region 5 the film would be suitable for 10 Gbit/in.^{2} longitudinal recording (15). Reprinted with permission of the authors and the Institute of Electrical and Electronic Engineers.

Approaches to making higher-density media are centered on increasing K to improve thermal stability and increasing M_s by composition modification to increase signal strength, while maintaining small grain size in order to minimize noise. K is controlled by modifying the film or particle composition, for instance, by adding Pt to the CoCr-based alloys used in hard-disk media, or by cobalt doping of iron oxide particles or by increasing particle aspect ratios for flexible media. Since K is affected by the processing conditions of the material, its value for thin films and for bulk materials may be different. K and M_s cannot be increased arbitrarily without making the medium more difficult to write, so the choice of medium parameters is related to the design of the recording head, particularly the saturation magnetization of the pole pieces (34).

CONCLUSIONS

Although considerations of switching behavior and thermal stability apply to all types of magnetic recording media, a great deal of attention is now being focused on thermal stability in hard-disk media, because hard-disk systems have the highest storage density. In the quest to produce higher density hard-disk media, there has been a continuing trend to increase coercivity and anisotropy and to reduce magnetic film thickness, in order to reduce the transition width and increase the linear density. Grain size has simultaneously decreased in order to reduce the transition noise. As the superparamagnetic limit is approached (i.e., the thermal decay of the signal amplitude becomes significant with reducing grain size) it will be necessary to continue to increase the anisotropy of the materials used. This makes the medium more difficult to write, so that recording heads are required to produce a higher write field. High anisotropy materials, including barium ferrite (43) and Co–rare earth compounds such as CoSm (44), are being considered for advanced recording media. At present there are significant fabrication problems. Ferrite films, for instance, require high-temperature processing that is not compatible with the use of aluminum hard-disk substrates. However, there is intense study of the fabrication and properties of these materials. Simultaneously there are developments in high saturation materials for recording heads, such as iron nitrides, in order to write the media (45).

Existing thin-film hard-disk longitudinal media materials are predicted to be capable of supporting recording densities of at least 40 Gbit/in.^{2} (34,46). This limit will likely be higher in practice as the aspect ratio of the bits is reduced by reducing the track spacing faster than the linear bit spacing. For higher densities this evolutionary development will ultimately be limited, and new data storage schemes may be introduced. There is considerable research on perpendicular hard-disk media, which are believed to have superior high-density noise properties and thermal stability (42), but so far perpendicular hard-disk media have had few commercial applications. On a longer developmental time scale, one possible scheme is the use of patterned media, in which data are stored in discrete patterned magnetic domains (46,47). These patterned media may be writtten and read by ultrasmall recording heads or by probe tips based on MFM technology. Since the boundaries of these bits are physically defined, there is no transition noise, and the constraints on the coercivity and grain size of the medium are reduced. The superparamagnetic limit then refers to the size of the bit rather than to the size of the grains of which it is composed, allowing a very high recording density to be achieved.

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C. A. Ross
Massachusetts Institute of Technology
M. E. Schabes
IBM Almaden Research Center
T. Nolan
Komag, Inc.
K. Tang
IBM Research Laboratories
R. Ranjan
Seagate Magnetics
R. Sinclair
Stanford University