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Modeling magneto-optical domain erasure without cylindrical symmetry

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We describe a technique for modeling domain dynamics in the context of thermomagnetic magneto-optical recording. The new feature of our model is that no assumption of cylindrical symmetry is required. We illustrate the potential of our technique by applying it to domain erasure on a moving disk.

I. INTRODUCTION

The goal of this paper is to present a novel technique for modeling the dynamics of magnetic domains in the context of magneto-optical data storage. Its essential feature is that neither the domains, nor the laser-induced thermal profiles need be cylindrically symmetric. Hence, realistic data storage situations can be treated. Yet the computing requirements of our model are quite modest so that simulations can easily be performed on a desktop workstation. We illustrate this aproach by treating an example of domain erasure on a moving disk.

Writing and erasure are the two components of direct overwrite, the process by which a data track is overwritten in a single pass. In conventional magnetic disk storage devices direct overwrite is achieved with a modulated magnetic field which switches domains irrespective of their original orientation. In order to obtain sufficient field strength at the high frequency of the data rate, the head must be placed very close to the magnetic storage medium. A major advantage of magneto-optical data storage devices is that the head can potentially be relatively distant from the media. This facilitates media removability, for example. However, this advantage is currently bought at the cost of at least two passes per overwrite. On the first pass the applied magnetic field is oriented to erase the data track by laser-induced heating. On the second pass the applied field is reversed to allow the laser to write domains. Since the bias field is not switched at the data rate, a high-field, large inductance bias magnet can be placed comparatively far from the media.

Single-pass direct overwrite schemes would allow the data rates of magneto-optical devices to more closely approach those of conventional magnetic disk devices. Consequently a variety of such schemes have been proposed.[1–6] We confine our attention to rare-earth/transition-metal thin-film magneto-optical media, such as terbium-iron. These films are ferrimagnetic and have large perpendicular anisotropy, so that the magnetization is oriented perpendicularly to the plane of the film. The particular direct overwrite scheme we have in mind is based on domain erasure by wall surface tension driven collapse,[3] and this paper concentrates exclusively on the modeling of the erasure step.

Previous modeling of thermomagnetic direct overwrite has largely been confined to cylindrically symmetric geometries. A notable exception is the work of Mansuripur, who used a two-dimensional lattice of interacting magnetic dipoles to model domain nucleation and wall motion, without any restrictions on the geometry.[7] Unfortunately, the small cell size and two-dimensional domain representation imply that large computing resources are required by this approach.

In contrast to this work, our model represents the domain by a chain of points which define the domain wall. This one-dimensional representation of the domain greatly reduces the computer power required to run the model. However, an important difficulty with such a model, which we address, is the treatment of the collective nature of the wall motion: The motion of a wall segment is strongly influenced by the motion of adjacent wall segments so that the entire wall moves as a whole.

Our physical model of domain dynamics and its algorithmic implementation are discussed in Sec. II. In Sec. III we present some applications to domain erasure in noncylindrically symmetric situations, such as occur on a moving disk. We conclude by discussing how our model can be used and extended to further study the physics of direct overwrite.

II. THE MODEL

Building on the modeling of magnetic bubble dynamics,[8,9] several authors have analyzed the growth and collapse of magnetic domains under the assumption of cylindrical symmetry.[10–12] In such work the magnetic domains are taken to be circular, and the laser is assumed to induce circular temperature profiles centered on the domain. Most such work also assumes that the domain wall moves with infinite velocity so that it always evolves between stable, equilibrium radii. (Note that our earlier work did not make this assumption.[3])

In this paper we use the standard micromagnetic model[13] and assume zero domain wall width. The forces on a domain wall are then of three kinds: (1) Contractive "surface tension," due to the wall's positive energy density; (2) forces resulting from spatial temperature gradients, which induce spatial gradients in the (temperature-dependent) wall energy; (3) magnetic forces due to the film's demagnetizing field and any applied magnetic field. The essential new feature of our treatment is that it generalizes the earlier work on cylindrically symmetric domains to allow for domains of arbitrary shape. Our domains are polygons defined by a closed chain of points which define the domain wall (see Fig. 1).

The major difficulty faced by such a model is the nonlocal nature of domain wall motion. Sections of domain wall cannot move independently of each other. The movement of a particular section of wall will affect, and be affected by, the

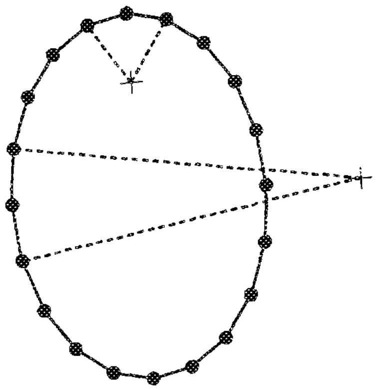

FIG. 1. An elliptical magnetic domain wall as represented in our model. The solid circles are the domain wall points, and the edges joining them define the domain wall. The dashed lines are radii of the circular arcs associated with two of the wall points. Each point, together with its two neighbors, defines a circle. The centers of two of these circles are marked with crosses. Since different parts of the elliptical domain have different curvatures, the associated circular arcs have different radii.

movement of adjacent sections of the wall. In cylindrically symmetric models, the circular domain expands or contracts as a whole, and this problem does not explicitly arise. In contrast, to determine the movement of a domain wall point in noncylindrically symmetric models requires knowing how the adjacent wall points will move.

To break the circular dependence we make an assumption about the motion of adjacent points. An important constraint is that the known motion of circularly symmetric domains must be reproduced. This leads us to a minimal assumption consistent with this constraint. We assume that the domain wall through the point under consideration and its two neighboring points is an arc of the unique circle passing through them. The dynamics of the central point is determined by the dynamics of this arc. The radius of the arc expands or contracts as under the assumption of cylindrical symmetry, but with the radial dependence of the various variables being that on the radius through the central point. Since we are concerned with small wall movements over each time step only the parameter dependence very near the wall is important.

Let R be the radius of the arc through the central point and its neighbors, x_i the coordinate vector of wall point i, P ($\mathrm{N\,m^{-2}}$) the wall pressure, σ_w ($\mathrm{J\,m^{-2}}$) the domain wall energy density, M ($\mathrm{A\,m^{-1}}$) the magnetization (with sign corresponding to the domain interior) and H ($\mathrm{A\,m^{-1}}$) the total demagnetizing plus applied magnetic field. Then the above assumption implies that the pressure on the wall at point i is[10]

$$P(x_i) = \frac{\sigma_w(x_i)}{R} + \left(\frac{d\sigma_w}{dR}\right)_{x_i} - 2\mu_0 M(x_i)H(x_i), \qquad (1)$$

and its direction is along the radius from the central point to the circle's center. We emphasize that our use of this formula requires no symmetry assumptions. It is based on a reasonable assumption about the coupled dynamics of adjacent wall points.

The wall point is assumed to move at a velocity v proportional to the excess of wall pressure P over the local coercive pressure $P_c = 2\mu_0 M(x_i)H_c(x_i)$ until it reaches a saturation wall velocity $v_{\rm sat}$:

$$\begin{aligned} v &= 0, && \text{if } |P| < |P_c|,\\ &= c_v\,\mathrm{sign}(P)|P - P_c|, && \text{if } |P| > |P_c|,\\ &= v_{\rm sat}, && \text{if } c_v|P - P_c| > v_{\rm sat}. \end{aligned} \qquad (2)$$

Here c_v [$\mathrm{ms^{-1}(N\,m^{-2})^{-1}}$] is the constant of proportionality between the pressure and velocity and $H_c(x_i)$ ($\mathrm{A\,m^{-1}}$) is the coercivity at point i.

Our algorithm for the thermomagnetic dynamics of arbitrary shaped domains determines the movement of each wall point over the current time step as follows: First, the current temperature profile in the magneto-optical layer is calculated. We use an approximate method due to Holtslag,[14] which is accurate to better than 10% when the thermal diffusivity of the magneto-optical layer is much greater than that of the adjacent layers. A more accurate solution is probably unnecessary given the large uncertainties in the thermal parameters of thin films, compared with those of bulk materials. Next, the demagnetizing field at each wall point is calculated. Since this requires an integration over the whole two-dimensional film for each wall point, it is by far the most time-consuming step. Then the radius and center of the circular arc on which the current point and its neighbors lie are found. Finally, the local pressure and wall velocity are calculated using Eqs. (1) and (2), and each point moved the appropriate amount along the radius of its arc. We expect this model to converge to the correct dynamics as the number of wall points is increased and the time step decreased. As required, it does reproduce the correct dynamics in cylindrically symmetric situations.[3]

If the time step is too large a spatially zig zag, time oscillatory, numerical instability is possible. The onset of this instability is characterized by a situation where alternate wall points are inside and outside the correct domain wall. Since alternate wall points are then on highly curved concave or convex arcs, the wall surface tension which dominates the subsequent dynamics causes them to move in opposite directions. If the time step is too large this movement allows the points to move across the correct domain wall. Then the wall points oscillate across the correct domain wall at each time step. As the number of wall points is increased the time step must be decreased to avoid this instability. With a fixed time step, the density of wall points on the domain wall must not become too high.

III. MODELING RESULTS

As an illustration of the power of our model, we now present selected results of simulations of domain erasure on a moving disk. This work extends previous modeling, which has been confined to the static disk case, to the realistic situation of a spinning disk. It also serves to demonstrate the success of our model in simple noncylindrically symmetric situations. In addition we show how practical problems such as the effects of a laser transverse tracking error on the erasure process can be handled by this technique.

The examples presented in this section are schematic since they do not correspond to any particular recording medium. The magnetic parameters we chose to test our model correspond to a hypothetical magneto-optical material having sufficiently low coercivity and high wall energy density that domain collapse driven by wall surface tension can occur. The actual magnetic parameters used in our simulations are graphed in Fig. 2. The assumed thermal properties of the magneto-optical film and its substrate and overcoat are given in Table I.

Domain wiring is facilitated by an applied write bias magnetic field. Direct overwrite requires both writing and erasing on a single pass. So our domain erasures are run in the presence of a 2×10^{4} A m^{-1} (250 Oe) magnetic field favoring write. Our present simulations do not include the domain writing process, however, so we arbitrarily chose an initial circular domain 0.5 μm in radius.

Figure 3 shows snapshots of domain erasure on a disk moving at 10 ms^{-1}. The domain wall points are shown as solid circles and the enclosed domain area is shaded. Also shown are the temperature contours induced by the erasing laser pulse. This example assumes 6 mW of laser power to be absorbed by the magneto-optical layer. On the moving disk the domain collapse starts on the leading side of the domain, since it is heated first. This leads to noncircular domain shapes. Otherwise the collapse occurs essentially as in the static disk case.

When the disk velocity is increased to 20 ms^{-1}, the laser power of 6 mW is no longer high enough to induce collapse. Erasure fails because of a combination of decreased temperatures, with consequent increased coercivities, and insufficient time at the elevated tmeperatures for collapse to proceed fully. Increasing the laser power to 7 mW allows collapse to occur again.

If the laser is off track in the transverse direction by 0.1 μm the erasure fails, as is shown in Fig. 4. This failure is due to insufficient heating on the domain's far side. This part of the wall remains close to the compensation temperature contour and hence experiences high coercivity, which prevents collapse. Erasure is successful if the transverse displacement is reduced to 0.05 μm or if the laser power is increased to 7 mW. In each case the compensation temperature contour is moved away from the far domain wall, decreasing the coercivity there and allowing the collapse to proceed.

These results demonstrate the applicability of our technique to modeling domain erasure on a moving disk and addressing practical problems such as offtrack heating. A variety of further applied physics issues can potentially be addressed by this model. For example by allowing for multiple domains in the model the physics of high domain packing density could be analyzed, permitting us to investigate important issues such as thermal crosstalk and interdomain magnetic interactions. Future work will also include the do-

TABLE I. Parameters used in the model to produce Figs. 3 and 4.

Parameter	Value
Time step	0.1 ns
Write bias magnetic field	-2×10^{4} A m^{-1}
Velocity/pressure proportionality, c_v	0.01 ms^{-1} (N m^{-2})$^{-1}$
Saturation wall velocity, v_{sat}	20 ms^{-1}
Initial domain radius	0.5 μm
$M-O$ layer thickness	100 nm
Laser beam radius	0.5 μm
Absorbed laser power	6 mW
Ambient temperature	300 K
$M-O$ compensation temperature	390 K
$M-O$ Curie temperature	530 K
$M-O$ thermal diffusivity	1.3×10^{-5} m^{2} s^{-1}
$M-O$ heat capacity	3.6×10^{6} J m^{-3} K^{-1}
Substrate thermal diffusivity (PMMA)	1.2×10^{-7} m^{2} s^{-1}
Substrate heat capacity (PMMA)	1.7×10^{6} J m^{-3} K^{-1}
Overlayer thermal diffusivity (glass)	7.5×10^{-7} m^{2} s^{-1}
Overlayer heat capacity (glass)	2×10^{6}

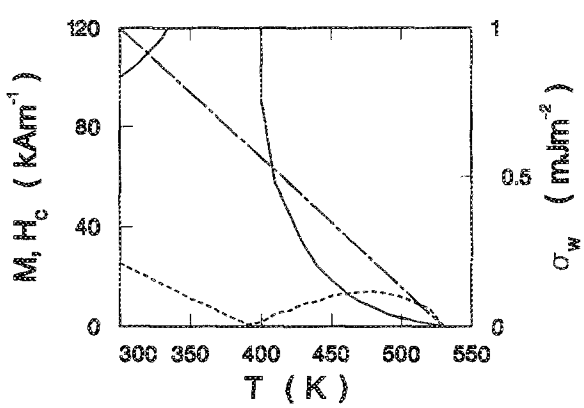

FIG. 2. Magnetic parameters as a function of temperature T, for the hypothetical magneto-optical film used to produce Figs. 3 and 4. M (dashed line) is the absolute value of the saturation magnetization (the magnetization is assumed negative below the compensation temperature), H_c (solid line) is the coercivity, and σ_w (chain dashed line) is the domain wall energy density.

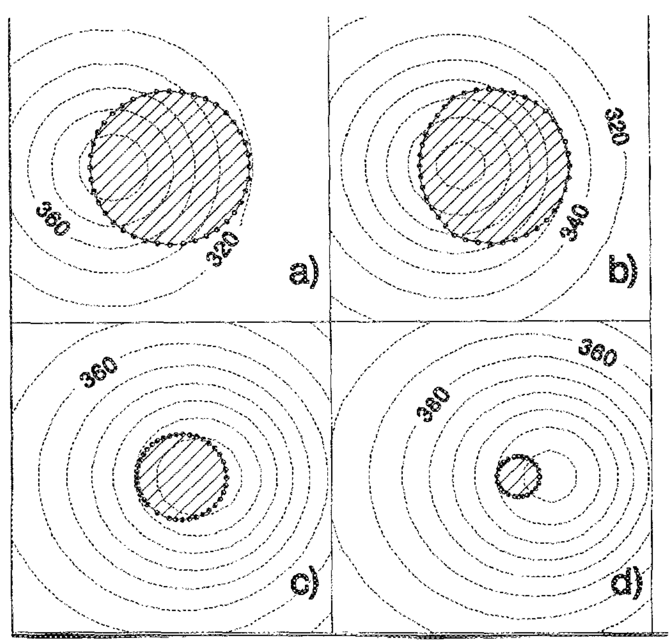

FIG. 3. Snapshots of the erasure of a domain on a disk moving at 10 ms^{-1}. The domain wall points are shown as solid circles and the domain interior is shaded. The dashed curves are temperature contours, 20 K apart. Each figure box is 2×2 μm. The four figures are snapshots at the following times after the start of the pulse: (a) 20, (b) 40, (c) 80, (d) 100 ns. The domain is fully collapsed by 110 ns. The pulse was started when its center was 0.5 μm to the left of domain center. Note that in (c) and (d) some wall points have been deleted by the algorithm in order to avoid the instability described at the end of Sec. II. For model parameters see Table I and Fig. 2.

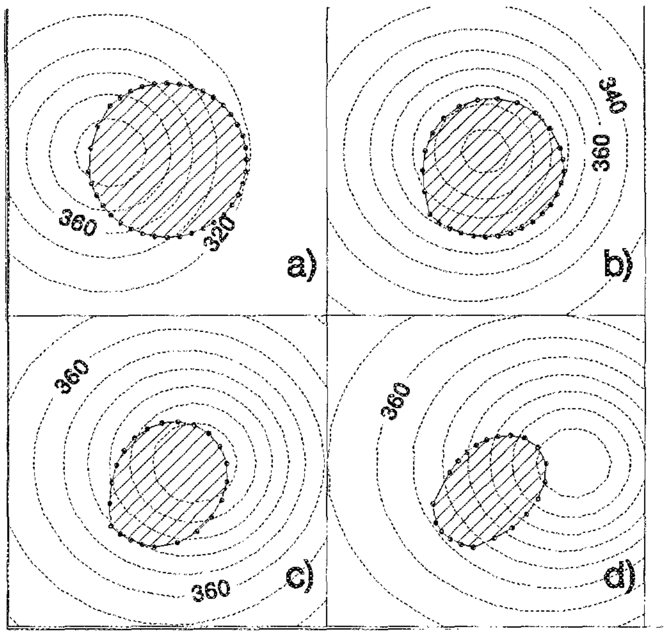

FIG. 4. Snapshots of failed domain erasure on a disk moving at 10 ms^{-1}. The erasure fails due to a 0.1-μm transverse (vertical) displacement of the laser beam from the track through the domain center. The four figures are snapshots at the following times after the start of the pulse: (a) 20, (b) 60, (c) 80, (d) 120 ns. For further explanation see the caption of Fig. 3.

main nucleation process in our model. This will enable us to treat the writing step as well as domain erasure in direct overwrite schemes.

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