AIP Journal of Applied Physics

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Citation: Journal of Applied Physics **69**, 4844 (1991); doi: 10.1063/1.348250
View online: http://dx.doi.org/10.1063/1.348250
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/69/8?ver=pdfcov
Published by the AIP Publishing

Coercivity of domain-wall motion in thin films of amorphous rare-earth–transition-metal alloys

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Computer simulations of a two-dimensional lattice of magnetic dipoles are performed on the Connection Machine. The lattice is a discrete model for thin films of amorphous rare-earth–transition-metal alloys with application to erasable optical data-storage systems. Simulated dipoles follow the dynamic equation of Landau, Lifshitz, and Gilbert under the influence of an effective magnetic field arising from local anisotropy, near-neighbor exchange, classical dipole-dipole interactions, and externally applied fields. By introducing several types of defects and inhomogeneities in the lattice, we show that the motion of domain walls can be hampered in various ways and to varying degrees.

I. INTRODUCTION

Magnetization reversal in thin films of amorphous rare-earth–transition-metal alloys is of considerable importance in erasable optical data storage.[1] The success of thermomagnetic recording and erasure depends on the reliable and repeatable reversal of magnetization in micrometer-size areas within the storage medium. A major factor entering the thermomagnetic process is the coercivity of the magnetic medium. The purpose of the present paper is to investigate the coercivity of wall motion at the submicrometer scale using large-scale computer simulations. There exists a substantial literature addressing the various aspects and mechanisms of coercivity in thin films; the interested reader may consult Refs. 2–5.

Our computer simulations were performed on a two-dimensional hexagonal lattice of magnetic dipoles following the Landau–Lifshitz–Gilbert equation. In addition to interacting with an externally applied field, the dipoles were subject to effective fields arising from local uniaxial anisotropy, nearest-neighbor exchange, and long-range dipole-dipole interactions. Periodic boundary conditions were standard in these simulations. Details of the micromagnetic model have been previously published[6–8] and will not be repeated here. Suffice it to say that the massive parallelism of the Connection Machine on which these simulations were performed, together with the fast Fourier-transform algorithm[8] which was used to compute the demagnetizing field, enabled us to accurately simulate a large (256×256) hexagonal lattice of dipoles. Since the lattice constant was chosen to be 10 Å, the total area of the simulated lattice corresponds to a 0.256 μm$\times$0.222 μm section of the magnetic film.

Nucleation coercivity was addressed in a previous paper[9] where it was shown that for a uniform material the fields required to initiate the reversal process are generally higher than those observed in practice. Various submicrometer-size "defects" were then introduced in the magnetic state of the lattice and the values of nucleation coercivity corresponding to different types, sizes, and strengths of these defects were computed. We found, for instance, that voids have insignificant effects on the value of the nucleation field, but that reverse-magnetized seeds, formed and stabilized in areas with large local anisotropy, can substantially reduce the coercivity. Similarly, the presence of spatial variations in the magnetic parameters of the material, such as random axis anisotropy, was found to affect the coercivity of nucleation.

Random spatial fluctuations and structural/magnetic defects also create barriers to domain-wall motion. These barriers are overcome only when sufficiently large magnetic fields (in excess of the so-called wall-motion coercivity) are applied. Simulations reveal that wall coercivity in amorphous RE-TM alloy films is generally less than the corresponding nucleation coercivity. This finding is in agreement with the experimentally observed square shape of the hysteresis loops in these media. The strength of wall coercivity of course depends on the size and type of fluctuations and/or defects. The results reported in the next section are intended to clarify some of these relationships.

II. STRUCTURE AND MOTION OF DOMAIN WALLS IN THE PRESENCE OF AN EXTERNAL FIELD

The following set of parameters used in our simulations is typical of amorphous films of TbFeCo in magneto-optical recording: saturation magnetization $M_s = 100$ emu/cm^3, anisotropy energy constant $K_u = 10^6$ erg/cm^3, exchange stiffness coefficient $A_x = 10^{-7}$ erg/cm, film thickness $h = 500$ Å, damping coefficient $\alpha = 0.5$, and gyromagnetic ratio $\gamma = -10^7$ Hz/Oe. In subsequent discussions the term "random axis anisotropy" is meant to imply that the anisotropy axes of the lattice are distributed randomly and independently among the lattice cells (or various groups of cells). By keeping the deviations from the Z axis below a certain maximum angle θ, the random assignment of axes preserves the perpendicular nature of the overall anisotropy. For brevity, θ will be referred to as the *cone angle*. Note that the random assignment of the anisotropy axes to individual lattice cells does not automatically result in rapid variations of the direction of magnetization in space. In fact, the strong exchange field in our simulations gives rise to a smooth distribution of the magnetization across the lattice, even when large cone angles are involved.

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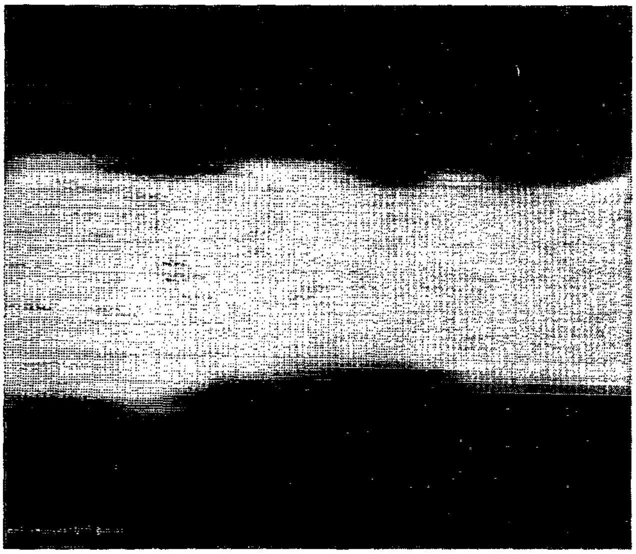

FIG. 1. Stripe domain in medium with random axis anisotropy (cone angle $\theta = 45°$) in the absence of an applied field.

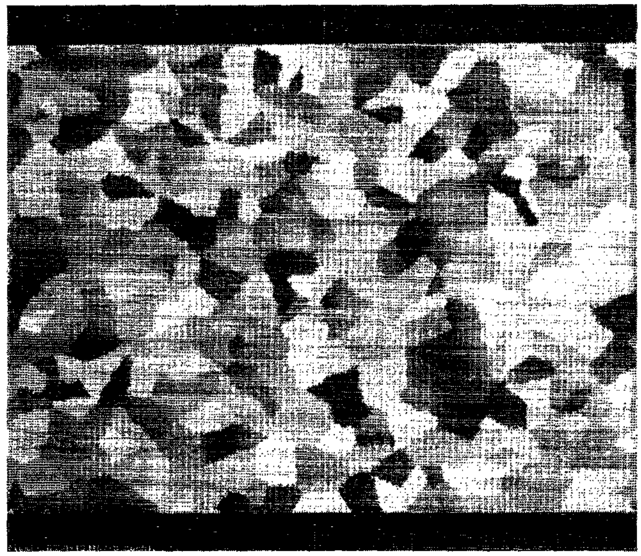

FIG. 2. Patchy lattice with 346 patches.

Figure 1 shows two domain walls in a medium with random axis anisotropy over individual lattice cells (cone angle $\theta = 45°$). Initially, the central band of the lattice was magnetized in the $+Z$ direction (white), while the remaining part was magnetized in the $-Z$ direction (black). When the lattice was allowed to relax for about 4.5 ns, the steady-state pattern in Fig. 1 was obtained. (Note that because of the imposed periodic boundary conditions, the physical situation depicted here is that of a periodic array of stripe domains, rather than just a single stripe, in an otherwise uniform medium.) A perpendicular field $H_z = -200$ Oe moves the two walls somewhat closer to each other, but fails to eliminate them; the force of demagnetization opposes the external field in collapsing the reverse-magnetized stripe. The stripe will collapse, however, under an applied field of $H_z = -1000$ Oe. In this example, the randomness in the lattice is clearly too weak to give the wall a significant coercivity. One way to achieve higher coercivity is to increase the correlation length of the fluctuations in space by introducing patches that are large compared to the wall width.

Figure 2 shows a typical lattice covered with 346 patches of random shape and size. These patches were created by selecting at random a number of lattice sites as seeds and growing outward from them (in a random fashion) until every site in the lattice belonged to one patch or another. By assigning different attributes to different patches, one can thus create spatial variations in the structure/magnetic properties of the lattice over length scales that are comparable to the patch size.

Figure 3(a) shows a stripe of reverse magnetization in the patchy lattice of Fig. 2. For the sake of clarity, the boundaries of the patches are highlighted in the figure. Each patch is assigned an axis of anisotropy, randomly and independently of all the others, with a cone angle of $\theta = 45°$. The walls in Fig. 3(a) are somewhat more jagged than those in Fig. 1, where the patches were essentially the size of an individual lattice cell. Under an applied field of $H_z = +1.5$ kOe, the walls in Fig. 3(a) move slightly and then come to equilibrium as shown in Fig. 3(b). (Studying the time evolution of $\langle M_z \rangle$, the average magnetization of the lattice along the z axis, we found that the initial $\langle M_z \rangle$, which is only slightly above zero, increases to about $0.2M_s$ in the first 0.5 ns after the application of the field, but stops growing at that point.) Compare this situation with the case corresponding to Fig. 1, where 1 kOe of applied field was sufficient for eliminating the stripe. Clearly, it is the patchy material, and not the demagnetizing force, which is responsible for blocking the wall motion. The wall-motion coercivity has thus increased as a result of increased correlation among the local easy axes. When the field was further increased to $H_z = +2$ kOe, it became possible to push the walls in Fig. 3(b) beyond the barriers and force them to wrap around the lattice boundary, collide with each other, and annihilate.

In order to understand the effect of the patch size on coercivity, we repeated the above simulation with a total of 1300 patches in the lattice. Again, we found that $H_z = 1.5$ kOe could not move the walls significantly, but that $H_z = 2$ kOe could. It is probably safe to assume, therefore, that the average size of the patch does not affect the coercivity in a substantial way, so long as it is larger than the width of the domain walls.

Figure 4(a) shows another strip of reverse magnetization in the patchy lattice of Fig. 2. This time, however, some of the patches have been made void by assigning the value of zero to their magnetic parameters. These void patches are shown as gray regions in the figure. (No special property is assumed for the dipoles at the void boundaries, their magnetic parameters being the same as those elsewhere in the lattice. Of course, no exchange field is exerted on the boundary dipoles from the neighboring cells on the void side, and the magnetic charges that accumulate on the void boundaries are automatically accounted for when the demagnetizing field is computed.) Other patches in the

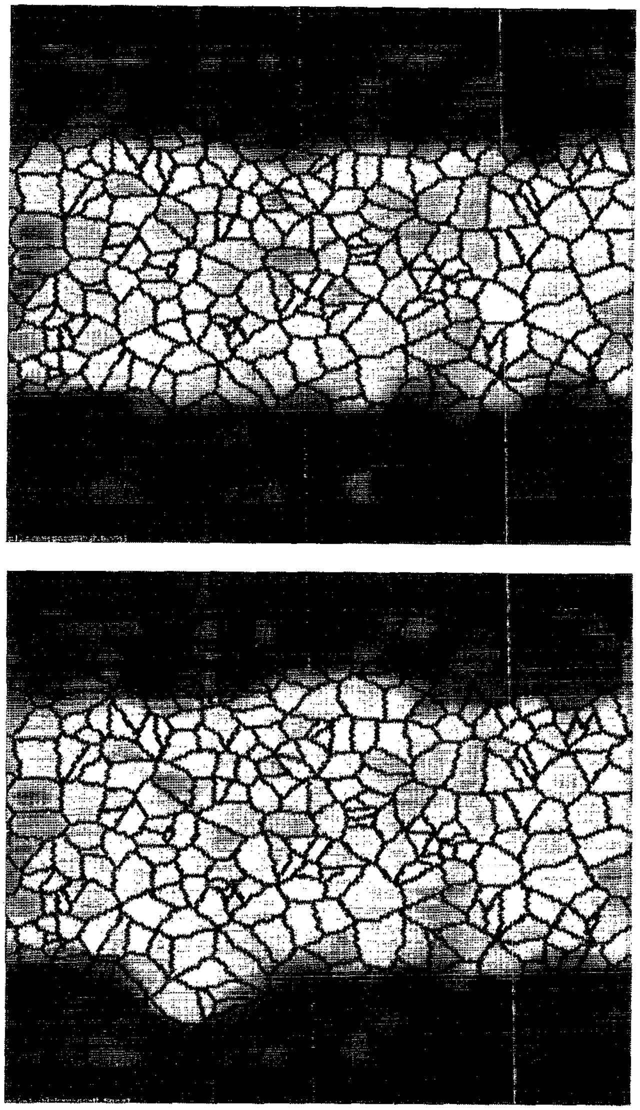

FIG. 3. Strip of reverse magnetization in the patchy lattice of Fig. 2. (a) The state of the lattice at $H_z = 0$. (b) At $t = 1.5$ ns after the application of a 1.5-kOe field.

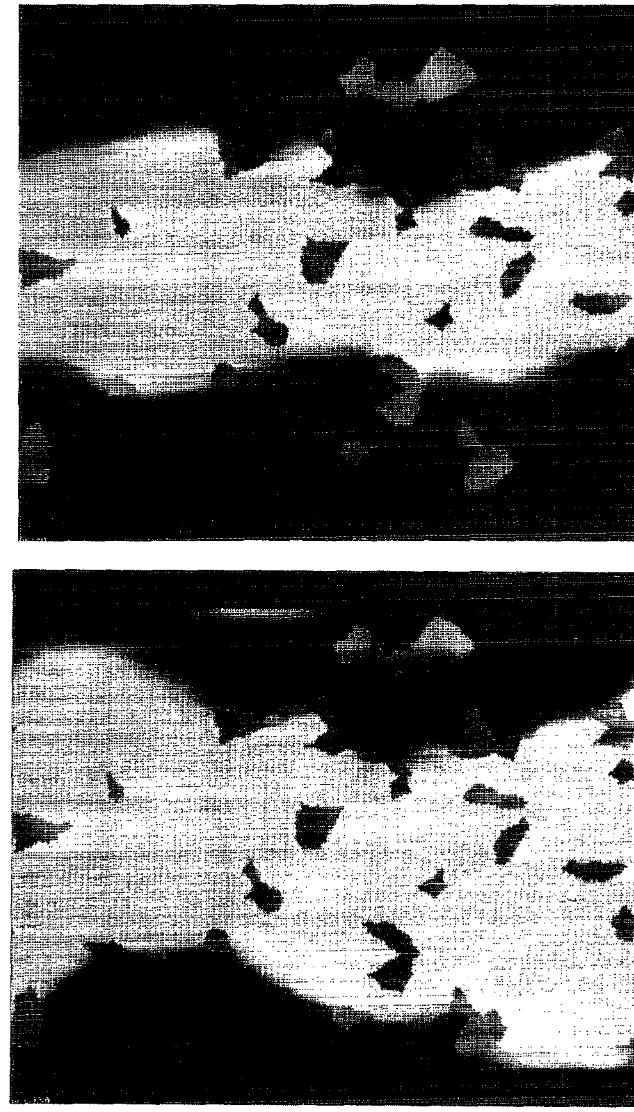

FIG. 4. Strip of reverse magnetization in a patchy lattice with voids. (a) At $H_z = 0$. (b) After $t = 5$ ns under the applied field of $H_z = 1.5$ kOe.

lattice of Fig. 4 are similar to each other in their magnetic properties except for the value of the anisotropy constant K_u, which varies randomly and independently from patch to patch. (The standard deviation of these variations is 20% of the average value of K_u.) No other spatial variations in the parameters have been assumed, and in particular, all axes of anisotropy are perpendicular (i.e., $\theta = 0$).

The walls in Fig. 4(a) have automatically adjusted themselves to minimize their lengths by attaching to the voids in the neighborhood. Minimization of the length is tantamount to minimization of total wall energy and is therefore favored by the magnetic system under consideration. Figure 4(b) shows the equilibrium state of the lattice under an applied field of $H_z = +1.5$ kOe. Apparently, the walls have continued to seek voids to attach onto, while expanding in response to the field. The total energy of the magnetic lattice during this period was marked by slow declines, characteristic of continuous wall motion, and rapid drops, corresponding to detachments from or attachments to the voids. It is thus observed that voidlike defects in real media can create jagged domain boundaries, increase the coercivity of wall motion, and cause discontinuities in the propagation process.

We studied several other types of defects and found their consequences for wall motion to be more or less the same as what has been described in this paper. A comprehensive report of this work appears in Ref. 10.

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