Fast reversal dynamics in perpendicular magnetic recording media with soft underlayer

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Reversal dynamics in perpendicular magnetic recording media is investigated using finite element micromagnetic simulations. The results show that gyromagnetic precession plays an important role during the magnetization reversal of both the soft underlayer and the data layer. Magnetization reversal within the soft underlayer starts at positive applied field due to its low anisotropy and high demagnetization field. The switching of the data layer starts at an applied field of about $-0.3\,H_{k,\mathrm{DL}}$, where $H_{k,\mathrm{DL}}$ is the anisotropy field of the data layer. At finite temperature, thermal activation reduces the dynamic coercivity. However, this effect is smaller than the change of the dynamic coercivity found by varying the Gilbert damping parameter, α. Media dynamic coercivity was found to increase significantly when α was decreased from 0.1 to 0.01. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1450832]

I. INTRODUCTION

Recent research on the reversal dynamics of soft magnetic thin films showed that gyromagnetic precession can strongly affect magnetization dynamics at the subnanosecond time scales.[1] It is therefore important to study the micromagnetic dynamic processes in perpendicular magnetic recording media, which consist of a magnetically hard data layer (DL) and a magnetically soft underlayer (SUL) as this composite structure of magnetic thin films has the potential of providing high recording densities (>100 Gb/in^2) at high data rates (about 1 Gb/s or larger). Even shorter time scales are involved in the record process when the rise time of the write current in the record head is considered, which—even at modest data rates—must not be more than a fraction of a nanosecond (100–300 ps). The fast dynamic response of the data layer and of the SUL is therefore important for achieving high performance in perpendicular magnetic recording.[2] In this article we apply magnetic fields to a small sample of a soft–hard composite layered structure with sweep times between 1 ns and 4 ns. Computing the magnetization response we obtain dynamics hysteresis loops at various temperatures and materials parameters and study the details of the micromagnetic magnetization processes. In Sec. II we describe the sample geometry, the material parameters used in the simulations and the micromagnetic model developed for these simulations. In Sec. III dynamic magnetization loops are shown as well as magnetization configurations at various stages of the reversal process at $T=0$ and $T=350$ K.

II. MICROMAGNETIC MODEL

In this article we simulate magnetization processes in a magnetic thin film described in Fig. 1. The perpendicular recording medium consists of a data layer, an exchange break layer, and a soft underlayer. The grains in the data layer have an average grain size of 7 nm are obtained from a Voronoi tesselation algorithm. The thickness of the data layer and the exchange break layer are 15 nm and 5 nm, respectively. The thickness of the soft underlayer is 60 nm. The finite element model consists of more than 50 000 tetrahedral elements with a size in the range from 2 nm to 25 nm.

Within each finite element the direction cosines of the magnetization vector, m_i, and the magnetic scalar potential, U, are interpolated by a linear function. The magnetostatic field, $\mathbf{H}_d=-\nabla U$, is calculated by solving the magnetostatic

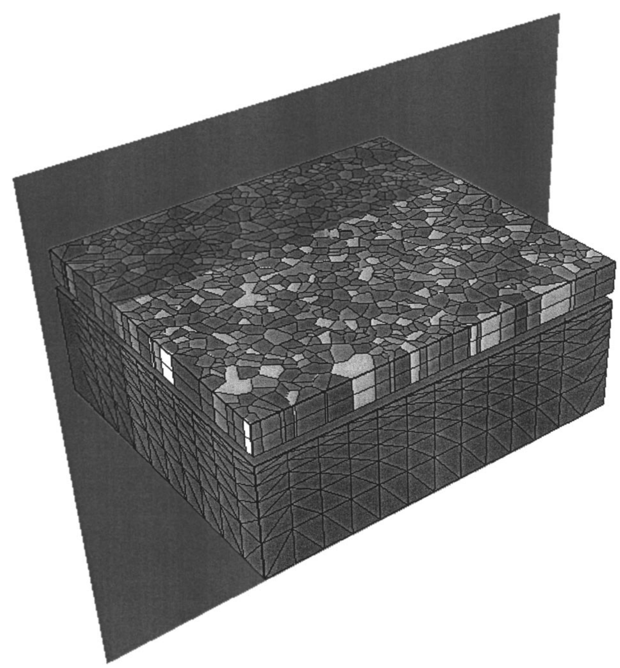

FIG. 1. Finite element model of a perpendicular recording medium consisting of a granular data layer and the soft underlayer. The shaded area denotes a slice plane for plotting the magnetization distribution (see Figs. 3 and 4).

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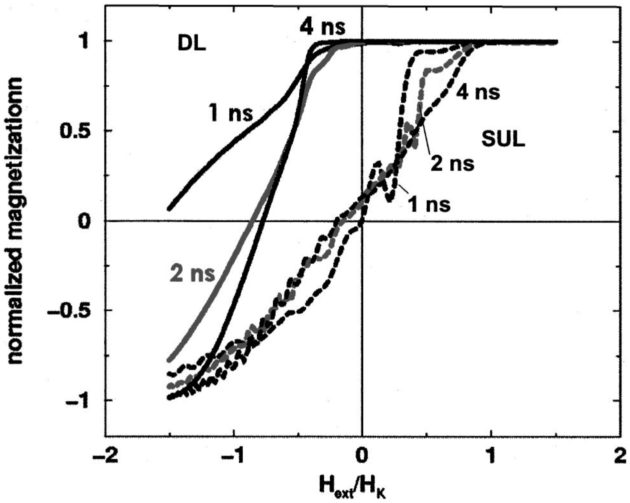

FIG. 2. Calculated demagnetization curves of the perpendicular medium for different sweep times of the external field. The field decreases from 1.5 H_k to -1.5 H_k in 4 ns, 2 ns, and 1 ns, respectively. H_k denotes the anisotropy field of the data layer grains. The solid lines refer to the magnetization of the data layer, whereas the dashed lines give the magnetization of the soft underlayer.

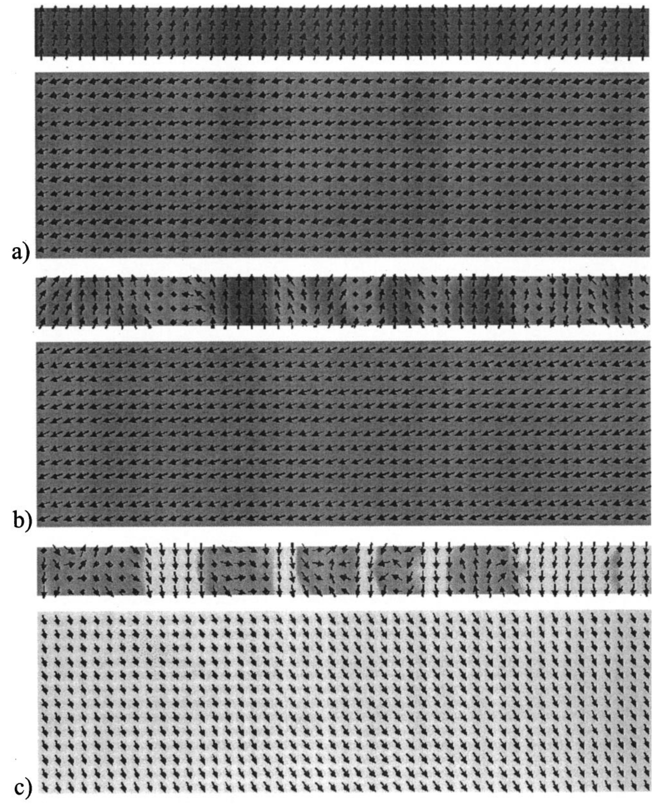

FIG. 3. Transient magnetization states during the dynamic switching of the data layer and the soft underlayer at a temperature, $T=0$ K. The sweep time τ was 4 ns. The images refer to the magnetic states after $t=2.26$ ns, $t=2.45$ ns, and $t=3.24$ ns.

boundary value problem for U. To account for the boundary conditions at infinity we apply a hybrid finite element/boundary value problem.[3] The boundary element method involves fully populated matrix $B_{n,n}$, where n is the number of nodes at the external surfaces of the finite element model. In order to reduce the size of the matrix, we extend the finite element mesh outside the magnetic layers and gradually increase the element size towards the external surfaces. Periodic boundary conditions are applied by matching the nodes at the external surfaces parallel to the film normal. In addition to the magnetostatic field, the numerical integration of the Landau–Lifshitz–Gilbert equation, requires the evaluation of the exchange field and the anisotropy field at the nodes of the finite element mesh. At node j, these contributions to the effective field are approximated by the negative derivative of the Gibbs free energy with respect to the magnetic moment at node j. Then the Landau–Lifshitz–Gilbert equation

$$\frac{\partial \mathbf{J}}{\partial t}=-\frac{\gamma}{1+\alpha^2}\mathbf{J}\times(\mathbf{H}_{\mathrm{eff}}+\mathbf{H}_{\mathrm{th}})-\frac{\alpha}{1+\alpha^2}\mathbf{J}\times(\mathbf{J}\times(\mathbf{H}_{\mathrm{eff}}+\mathbf{H}_{\mathrm{th}})) \tag{1}$$

is solved using the CVODE package[4] for $T=0$ and the method of Heun[5] for $T>0$. In Eq. (1) $\mathbf{J}$ is the magnetic polarization, α is the Gilbert damping constant, γ is the gyromagnetic ratio, $\mathbf{H}_{\mathrm{eff}}$ is the effective field. $\mathbf{H}_{\mathrm{th}}$ is a random thermal field obtained from the fluctuation dissipation theorem. The thermal fluctuation field has zero mean in space and in time. In the data layer, the uniaxial anisotropy direction was assumed perpendicular to the film plane with a deviation angle up to 5°. The uniaxial anisotropy constant was $K_{u,\mathrm{DL}}=2.6\times10^5$ J/m^3. The magnetic polarization of the data layer was $J_{s,\mathrm{DL}}=0.6$ T and the integrain exchange was $A_{\mathrm{DL}}=5\times10^{-13}$ J/m. The soft underlayer has a weak uniaxial anisotropy in plane ($K_{u,\mathrm{SUL}}=4\times10^2$ J/m^3), a magnetic polarization of $J_{s,\mathrm{SUL}}=1$ T, and an exchange constant of $A_{\mathrm{SUL}}=10^{-11}$ J/m.

III. RESULTS

Figure 2 shows the computed demagnetization curves of the data layer magnetization, M_{DL}, and the soft underlayer magnetization, M_{SUL}, respectively. The soft underlayer starts reversal in the first quadrant at positive fields. The external field, H_{app}, applied at an angle of 1° with respect to the film normal, is varied linearly from $+1.5$ H_k to -1.5 H_k (data layer anisotropy field) within the sweep time, τ. The anisotropy field was held constant in all simulations and the sweep time was varied from 1 ns to 4 ns. For all sweep rates magnetization reversal in the soft underlayer started at the same critical field but the rate at which reversal occurs is different. For $\tau=4$ ns the SUL demagnetization curve shows a steady decrease with constant slope. For $\tau<4$ ns we observe a delay before significant reversal processes begin in the SUL. The magnetization of the soft underlayer shows a steep decrease from 95% magnetization to 5% magnetization, then oscillates, and finally reversal proceeds at a significantly reduced slope $dM_{\mathrm{SUL}}/dH_{\mathrm{ext}}$. However, the data layer for all cases has a remanent squareness of 1. For $\tau=1$ ns the data layer demagnetization curve shows a more modest slope, starting at a field of 0.4 H_{ext}/H_k. The rate of change of the applied field is so large that the reversal process can-

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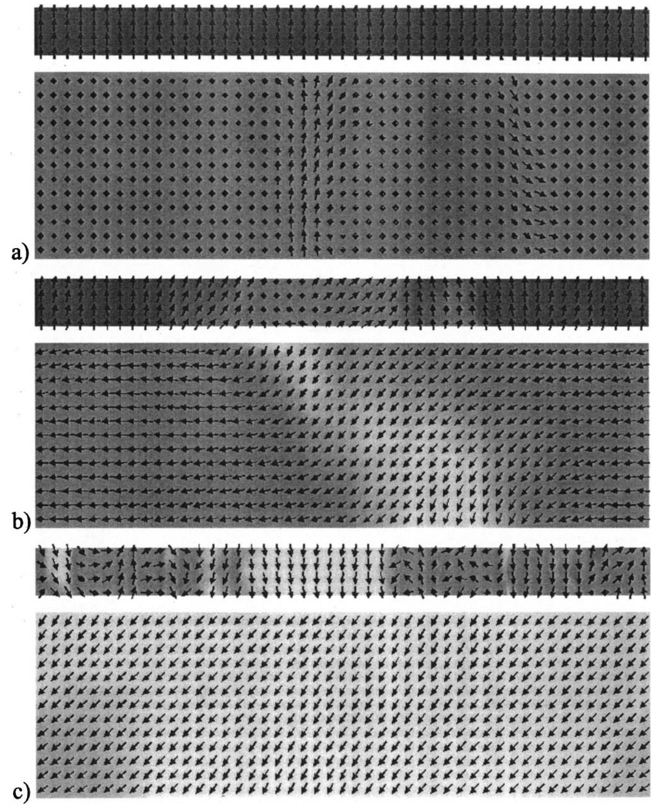

FIG. 4. Transient magnetization states during the dynamic switching of the data layer and the soft underlayer at a temperature, $T = 350$ K. The sweep time τ was 2 ns. The images refer to the magnetic states after $t = 0.75$ ns, $t = 1$ ns, and $t = 1.6$ ns.

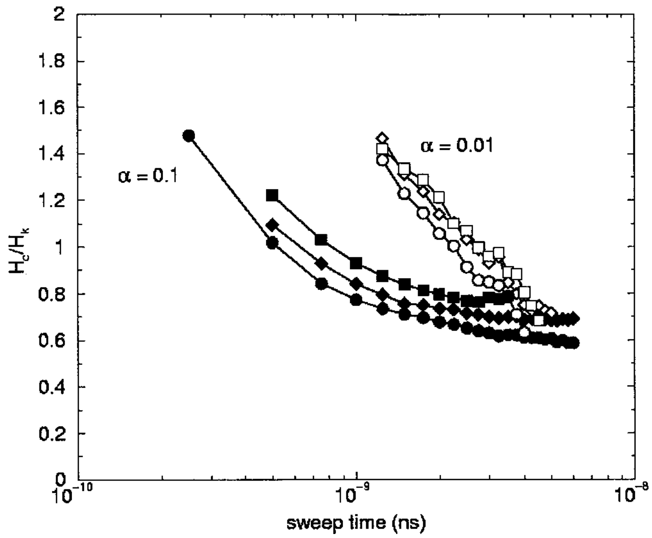

FIG. 5. Dynamic coercivity as a function of the sweep time for different Gilbert damping constant. Open symbols, $\alpha = 0.01$; closed symbols, $\alpha = 0.1$; diamonds, $T = 0$ K; squares, $K_{u,\mathrm{DL}}V/kT = 70$; circles, $K_{u,\mathrm{DL}}V/kT = 20$.

not keep pace with the applied field. The slope of $dM_{\mathrm{DL}}/dH_{\mathrm{ext}}$ is reduced. Increasing the sweep time from 1 ns to 2 ns leads to a larger slope with the onset of magnetization reversal occurring at lower field values. At 4 ns the onset of significant reversal is found at the largest applied field however, once reversal starts the slope of the demagnetization curve is the steepest.

Figure 3 shows a sequence of transient states during the reversal at $T = 0$. Significant precessional motion of the soft underlayer magnetization sets in when $|H_{\mathrm{app}}|$ falls below the demagnetizing field parallel to the field normal of the soft underlayer. At time $t = 0.2\ \tau$ to $t = 0.5\ \tau$ a large precessional cone is observed while the precessional axis rotates into the film plane [Fig. 3(a)]. During this initial motion of the magnetization within the soft underlayer, the magnetization in the data layer remains nearly saturated. Well pronounced precessional motion of the data layer magnetization starts at an external field of $-0.3\ H_k$. Nonuniform reversal process occur in the data layer due to the dispersion of the orientation of the anisotropy axes. At $t = 0.6\ \tau$ reversal of the data layer sets in [Fig. 3(b)]. Hard magnetic grains which have their easy axis almost parallel to the film normal are hard to reverse. Despite weak intergranular exchange coupling, $A = 5 \times 10^{-13}$ J/m, on the order of 10 grains collectively reverse. After $t = 0.8\ \tau$ some grains are found which are still magnetized in their original direction [Fig. 3(c)].

Figure 4 shows a sequence of transient states during the reversal process at $T = 350$ K. The sequence of soft underlayer precession, precessional motion within the data layer, and successive reversal of grains within data layer is similar to the simulations at $T = 0$. However, thermal fluctuations induce spin waves with a wavelength of about 80 nm in the soft underlayer and cause the data layer to reverse at lower external fields. At low external fields well pronounced multidomain states are found within the soft underlayer [Figs. 4(a) and 4(b)].

Figure 5 demonstrates the influence of magnetic dissipation on the dynamic coercivity. The plots shows curves computed for damping constants $\alpha = 0.01$ and $\alpha = 0.1$, and also for different stability ratios, $K_{u,\mathrm{DL}}V/k_BT$. This variation of the damping constant is seen to have a more pronounced effect on the dynamic coercivity than varying the temperature from $T = 0$ to $T = 350$ K. Small damping constants lead to a significantly larger dynamic coercivity for fixed sweep time.

ACKNOWLEDGMENT

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