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Simulations of magnetic hysteresis loops for dual layer recording media

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A Kinetic Monte-Carlo algorithm is applied to examine MH loops of dual-layer magnetic recording media at finite temperature and long time scales associated with typical experimental measurements. In contrast with standard micromagnetic simulations, which are limited to the ns-μs time regime, our approach allows for the direct calculation of magnetic configurations over periods from minutes to years. The model is used to fit anisotropy and coupling parameters to experimental data on exchange-coupled composite media which are shown to deviate significantly from standard micromagnetic results. Sensitivities of the loops to anisotropy, inter-layer exchange coupling, temperature, and sweep rate are examined. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4807501]

The use of stochastic micromagentic simulations based on the Landau-Lifshitz-Gilbert (LLG) equations is a standard technique for evaluating the dynamic evolution of magnetic structures at finite temperature.[1] However, the time steps required for reliable results are on the order of ps, which limit the total length of time that can be reasonably calculated. For example, in order to simulate a small magnetic structure over a 1 h period of time, it would require about a 100 000 years to complete the calculation using a fast modern computer (This is based on the estimation that a desktop computer using a central processing unit to calculate 10 μs of time evolution for a 1000 cell magnetic structure takes about 1 day to complete.) Typical experimental techniques used to measure MH loops, such as the Vibrating Sample Magnetometer (VSM), require a time span of minutes to hours. Algorithms based on simple Arrhenius-Neel scaling assumptions have been used in the past to extract meaningful results from LLG simulations for MH loops.[2–5] We recently published an alternative approach based on Kinetic Monte Carlo (KMC) methods which alleviates the problem of having to wait for rare events associated with stochastic processes that involve large energy barriers.[6] The focus of that work was on the simulation of single-layer recording media.

We present here results from an application of the method described in Ref. 6 to simulate MH loops of dual-layer exchange-coupled-composite (ECC) recording media at finite temperature and experimental sweep rates. ECC media composed of a high anisotropy (hard) layer exchange coupled to one or more lower anisotropy (soft) layers[7–10] was developed in an effort to overcome the problem of thermal stability and recordability associated with increases in areal density.[11,12]

A detailed comparison of experimental data and simulation results show that the resulting anisotropies are roughly linearly dependant on temperature. This agrees with experimental observations.[13] The sensitivity of the fitting parameters (hard and soft-layer anisotropies as well as inter-layer exchange) was also examined at low and high temperatures. In addition, these sensitivities also show a dependance on the sweep rate of the applied field. All of these results have implications for fitting techniques that require a rescaling of a low temperature simulation that uses a fast sweep rate.[3]

The application of the KMC method is based on the premise that the system is described by a sequence of metastable states separated by abrupt transitions between them in which a number of spins undergo a reversal. The transitions are due to the thermal fluctuations and typically occur on time scales much longer than dynamical time scales due to the magnitude of the energy barriers separating the metastable states. The time between successive reversals is determined using the Arrhenius Neel expression for the mean exit time of the individual spins, and includes the effect of the magnetostatic and exchange fields of the surrounding media. Following a reversal, the new metastable state is calculated by relaxing the system using the LLG equation and the mean exit times for the individual spins recalculated. Since the reversal of an individual spins can destabilise its neighbours, relaxation may result in a cascade process in which a cluster of spins undergoes a reversal. The KMC algorithm is implemented by repeating the following sequence of steps:

1. Relax the system into a minimum energy configuration. This is done using a conventional LLG algorithm.
2. Determine the energy barrier separating the minimum energy states for each spin.
3. Based on the energy barriers and attempt frequencies, calculate the mean exit times for each spin using the Arrhenius Neel expression.
4. From these transition rates, generate a stochastic variable that determines the time each spin will wait before undergoing a reversal.
5. Choose the spin with the lowest wait time, and generate a new configuration with the spin is in the new energy minimum.

The geometry studied corresponds to a simple dual layer exchange-coupled structure. The applied field producing the MH loop is oriented perpendicular to the plane. Each layer has a different anisotropy strength and in-plane exchange

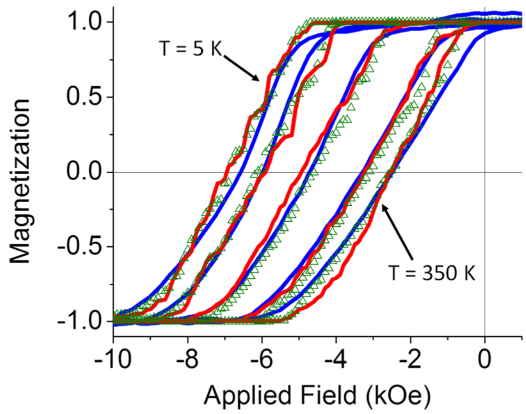

FIG. 1. Experimental (blue lines) and simulated MH loops for dual layer media at different temperatures of $T = 5$ K, 100 K, 200 K, 300 K, and 350 K. The simulations used field sweep rates of 11 Oe/s (red lines) and 1×10^9 Oe/s (green triangles) and were fitted independently by adjusting the interlayer exchange coupling between layers and the anisotropies of the two layers.

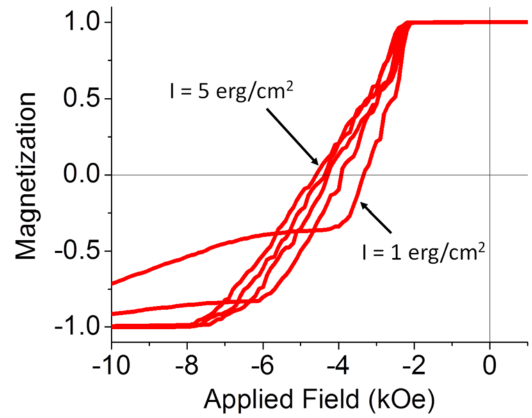

FIG. 3. Simulated MH-loops at zero temperature for different inter-later exchange values: $I = 1$, 2, 3, 4, and 5 erg/cm^2.

coupling between grains. The coupling between layers is defined by the inter-layer exchange constant, which we denote as I. Values used for the various parameters were guided by a number of experimental results. The layer with the weaker anisotropy, the soft layer, was assigned an anisotropy that was approximately half of the hard-layer value. The soft layer is more of a continuous film than the hard layer, having a larger the in-plane exchange. We choose in-plane exchange stiffness constants that are typical of this type of media: $A = 0.45\,\mu\text{erg/cm}$ for the soft layer and $A = 0.05\,\mu\text{erg/cm}$ for the hard layer. (Note that weak intra-layer exchange interactions typically improve recording performance.[14–16]) Saturation magnetizations of $M_1 = 540$ emu/cm^3 for the hard layer and $M_2 = 400\,\text{emu/cm}^3$ for the soft layer were used. The hard layer is taken to be 12 nm thick and the soft layer is 6 nm thick. Simulations were done on a system with 32×32 cells in each layer, with cells having lateral dimensions of $6\,\text{nm} \times 6\,\text{nm}$. (Uniformly magnetized grains in the soft layer thus have dimensions $6 \times 6 \times 6\,\text{nm}^3$ whereas they are $6 \times 6 \times 12$ nm^3 in the hard layer.) A small distribution in the anisotropy axis direction (perpendicular to the films) with a standard deviation of $\sigma = 3^\circ$ was assigned. In addition, Gaussian distributions were given to the saturation magnetization and anisotropy strengths with standard deviations of 10 percent. Fitting parameters were taken to be the layer anisotropies and the inter-layer exchange coupling. All results presented are averaged over five simulations using different random seed values.

Figure 1 shows a comparison of experimental and simulation results for MH loops at temperatures $T = 5$ K, 100 K, 200 K, 300 K, and 350 K. The results in Fig. 1 that used a sweep rate of 11 Oe/s correspond to one hour to complete a field sweep from 20 kOe to -20 kOe, typical of a VSM setup. Also shown in Fig. 1 are independently fitted simulation results using a fast sweep rate of 1×10^9 Oe/s, which requires 40 μs to complete a change in field value from 20 kOe to -20 kOe and corresponds to a conventional LLG simulation time scale.

The first fit was for the lowest temperature result, $T = 5$ K and the slow sweep rate of 11 Oe/s. The inter-layer exchange coupling was initially estimated to be 2 erg/cm^2. Based on the magnetization and coercive field observed in the experiment, we estimated an anisotropy value of $K_1 = 3\,\text{Merg/cm}^3$. Many runs were performed checking different ratios and strengths of the two anisotropies and different interlayer exchange. The goal was to best match the slope and the coercive field. The resulting nucleation field values showed discrepancies by as much as ± 1 kOe, but the coercive field results differed from the data by less than ± 100 Oe.

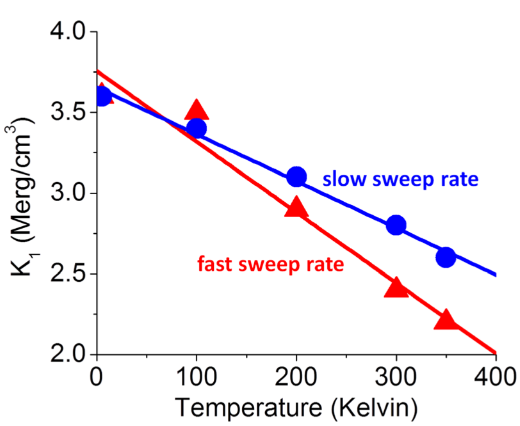

FIG. 2. A comparison of the required hard-layer anisotropy values which produced Fig. 1.

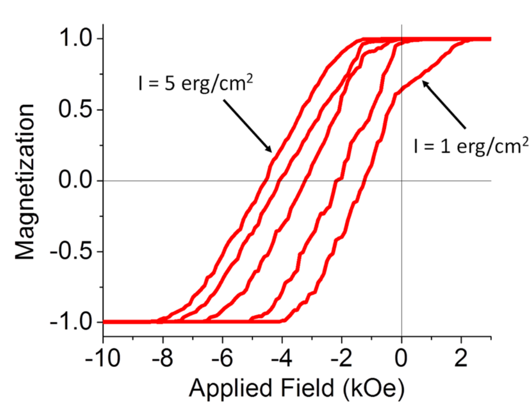

FIG. 4. Simulated MH-loops for T = 300 K. The inter-layer exchange coupling is different for each loop as in Fig. 3.

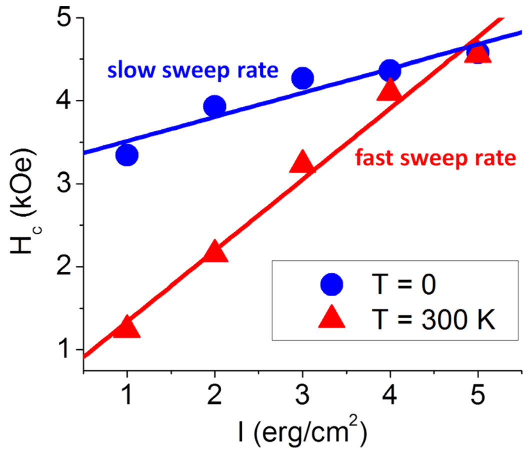

FIG. 5. The change of the coercive field vs inter-layer exchange corresponding to the MH loops shown in Figs. 3 and 4.

From all of the fitting trials, the result that best matched the shape and coercive field of the experimental data at the lowest temperature (5 K) had an anisotropy of $K_1 = 3.8$ Merg/cm^3 for the hard layer, $K_2 = 1.8$ Merg/cm^3 for the soft layer, with an inter-layer exchange of $I = 3$ erg/cm^2. A similar procedure for $T = 100$ K, 200 K, 300 K, and 350 K was performed. For simplicity, we assumed the same ratio of hard/soft anisotropy values of 0.47 and exchange interaction constant of 3 erg/cm^2. (This assumes an equivalent temperature dependence of the anisotropies of the two layers, governed by the assumption of equivalent grain Curie temperatures and intra-grain exchange values). This allowed only one independent fitting parameter, the hard layer anisotropy.

While the MH curves shown in Fig.1 for both sweep rates show good agreement with the experimental data, the parameters used to obtain these optimal fits was sweep rate dependent. The results for the fitted anisotropies are presented in Fig. 2. They show that while anisotropy at the lowest temperatures is almost independent of sweep rate, the approximately linear decrease in the anisotropy parameter with temperature is significantly greater for the low sweep-rate case than for the high-sweep case. Both the approximately linear decrease and the effect of sweep rate were consistent with our expectations. A similar behaviour was observed for the other fitting parameters.

Sensitivities of the loop shapes, in particular the coercivity, to variations in the anisotropies and interlayer exchange coupling were also examined. Baseline parameters were chosen to be the fitted values from the results at $T = 300$ K and slow sweep rate of 11 Oe/s. For the first group of simulations, all the parameters were kept constant except the inter-layer exchange, which was varied from $I = 1$ erg/cm^2 to $I = 5$ erg/cm^2. For the second group, all parameters were fixed, but the soft layer anisotropy was varied from 1.05 Merg/cm^3 to 1.57 Merg/cm^3, which is $\pm 20\%$ of the $T = 300$ K fitted value of $K_2 = 1.31$ Merg/cm^3. In the last group, the anisotropy of the hard layer was varied from 2.22 Merg/cm^3 to 3.34 Merg/cm^3. Simulations were performed at $T = 0$ K and 300 K. MH loops corresponding to several values of the inter-layer exchange constant for $T = 0$ K and $T = 300$ K are presented in Figs. 3 and 4, respectively.

These two sets of results are significantly different. In Fig. 3, the slow approach to saturation seen in the low exchange-value result is due to an effective decoupling of the two layers. The combined effect of the applied field and the demagnetizing field are sufficient to completely reverse the soft layer without completely switching the hard layer. This gradual switching of the hard layer with increasing field for low values of the exchange coupling gives rise to the prominent tail in the magnetisation curve shown in Fig. 3 for $I = 1$ erg/cm.

Fig. 5 summarizes the results of the sensitivity of the coercivity to the inter-layer exchange from both Figs. 3 and 4. The straight lines in Fig. 5 are a best fit to the $T = 0$ K and $T = 300$ K results assuming a linear relationship. While there is no *a priori* justification for such an assumption, it nevertheless provides a useful quantitative measure of the sensitivity. The slope of the fitted line for the low temperature case is 0.29 Oe cm^2/erg whereas in the high temperature case it is 0.86 Oe cm^2/erg. This large difference indicates that the system is much more sensitive to changes in the exchange coupling at high temperatures than at low temperatures. This same kind of analysis was done for the runs involving changing the anisotropy at both temperatures and both slow and fast sweep rates. The results are summarized in Table I.

From these results, we can make two main observations. The system is more sensitive to changes in the inter-layer exchange at higher temperatures than it is at lower temperatures. The opposite is true for the hard layer anisotropy. In addition, there are substantial differences in sensitivities at 300 K between slow and fast sweep rate results. In the case of inter-layer exchange, this difference in sensitivity is about a factor of two.

In conclusion, the importance of optimizing recording media through micromagnetic modeling has long been recognized by the hard drive industry. This requires models

TABLE I. Slopes for linear fits for the coercive field of simulated MH loops versus various exchange coupling and layer anisotropies. Results are presented for high and low temperatures as well as slow and fast sweep rates.

	$\Delta H/\Delta t = 11$ Oe/s		$\Delta H/\Delta t = 1 \times 10^9$ Oe/s		
Parameter range	Slope (0 K)	Slope (300 K)	Slope (0 K)	Slope (300 K)	Units
$1 \leq I \leq 5$ (erg/cm^2)	0.29	0.86	0.31	0.43	Oe cm^2/erg
$2.22 \leq K_1 \leq 3.34$ (Merg/cm^3)	2.19	1.45	2.05	1.08	kOe cm^{3}Merg
$1.05 \leq K_2 \leq 1.57$ (Merg/cm^3)	1.82	1.98	2.08	2.2	kOe cm^3/Merg

where microscopic parameters, such as anisotropy, exchange coupling, and distributions, are accurately determined. This can be a challenging exercise for media composed of multiple layers of various materials. The most widely used procedure to accomplish a correlation between models and experimental results is by fitting MH loops. While stochastic LLG simulations are very powerful, they are unable to simulate the long time scales associated with certain experiments. Our results demonstrate that fitting parameters can be in error by as much as 20% if a traditional micromagnetic approach is used. Further, we have shown that changing the hard layer anisotropy will produce greater changes to the simulation at lower temperatures than it will at higher temperatures. Conversely, adjusting the interlayer exchange produces greater changes at higher temperatures than at lower temperatures.

The sensitivities of the coercivity to the fitting parameters are also shown to be dependent on sweep rate. The KMC algorithm we have used matches LLG results for fast sweep rates, but also allows for calculations over long time scales.[6] The KMC method can therefore be used to model a greater variety of experiments with more reliable parameter fitting than through the use of dynamic LLG simulations based on scaling results from low temperatures and fast sweep rates.[3] Scaling that assumes the magnetic grains are non-interacting has been shown to be unreliable in the case of ECC media.[4] This work demonstrates that the use of the Kinetic Monte Carlo approach provides a means for the direct simulation of MH loops for multilayer recording media. Future work will involve the use of these fitted parameters to simulate other characterizations of the recording process such as long-term media Signal-to-Noise Ratio in ECC media.[6]

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