Time-dependent remanent coercivity in nanosecond switching in perpendicular media

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We have simulated the time-dependent remanent coercivity of a simple model of a perpendicular medium. The material parameters have been obtained by fitting to the data from quasistatic magnetometry measurements, and the pulse properties were obtained from stripline experiments. Our remanent coercivity results confirm the rise in coercivity at short times which has been found experimentally. We have also found a counter-intuitive increase of coercive field with decreasing initial remanent magnetization; a partially switched sample requires a stronger reverse field for complete demagnetization.

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As a result of recent increases in hard-disk data rates, the switching behavior of media at nanosecond time scales has become very relevant. One important parameter is the time-dependent remanent coercivity $H_{cr}(\Delta t)$, defined as the amplitude required for a reverse pulse of duration Δt to reduce a magnetized sample from the remanent state to magnetization $M = 0$. This quantity has been measured for very short pulses by stripline techniques[1].

In this paper we present some simulations of the switching process in perpendicular media, from which the time-dependent coercivity has been determined. The important features of our simulation are (1) we calculate the remanent coercivity (most previous work has calculated the ordinary coercivity, in the context of a hysteresis loop) and (2) we have determined material parameters by fitting to experimental data so that the resulting remanent coercivity can be directly compared to experiment. Simulations have been done previously having one of these two features, but we believe this is the first simulation satisfying both conditions. We have fitted our parameters to measurements on a CoCrPt sample[2] with a quasistatic coercivity of 2.5 kOe measured by VSM and with no soft underlayer (SUL).

Simulations of slower-speed switching of perpendicular media have been done for many years using quasi-static methods[3] and more recently faster switching has been studied using Landau-Lifshitz dynamics[4]. A recent simulation by Schrefl *et al* used a large system with random grain positions and a SUL to calculate the coercivity from a hysteresis loop[5] and studied the magnetization process of the SUL in the presence of recording heads[6].

The micromagnetic calculation is based on the standard Landau-Lifshitz (LL) equation for the time evolution of the magnetization $\mathbf{M}$ of a computational cell[7]

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H} - \frac{\alpha\gamma}{M_s}\mathbf{M} \times (\mathbf{M} \times \mathbf{H}) \quad (1)$$

The constant $\gamma = 17.6$ (KOe ns)$^{-1}$ $= 2.2 \times 10^5$ (A/m s)$^{-1}$ is the free electron gyromagnetic ratio, and we have taken the LL damping coefficient α to be 0.02. The total magnetic field $\mathbf{H}$ consists of an external field, an exchange field, an anisotropy field, the magnetostatic fields of other cells, and a random thermal field.

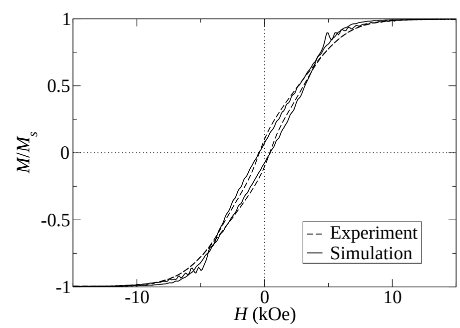

Figure 1: The best fitted hard axis hysteresis loop.

We have simulated a 160nm×160nm×20nm square slab with cubical cells of size 20 nm, consistently with the film thickness and average grain size determined by AFM imaging. The saturation magnetization M_s was determined by AGM measurement to be $4\pi M_s = 8.02$ kOe[8].

To determine the anisotropy field H_K we fitted the hysteresis loop along the hard (in-plane) axis. The simulated loop shows some wiggles when the system is approaching a saturated state. These oscillations in magnetization arises out of large precessional motion of still unswitched grains in presence of a strong switching field which would be averaged out in a larger system. The hard axis hysteresis loop for a coherently rotating system starts to drop from its saturated value at $H = H_K - NM_s$, where N is an effective demagnetizing factor. The factor N depends on the exchange interaction between the grains of the system: If the system consists of exchange decoupled needle-like grains, the demagnetizing factor $N = 0$; as we increase the exchange constant A the effective grain size increases and assuming a coherent rotation the factor approaches $N = 1$, the value for a infinite slab saturated along the perpendicular direction. Therefore, the hard axis loop also provides information about the exchange constant A. There is no hysteretic loss if the easy axis is fixed along the z axis (normal to the plane), so to fit the open experimental loop we have introduced a

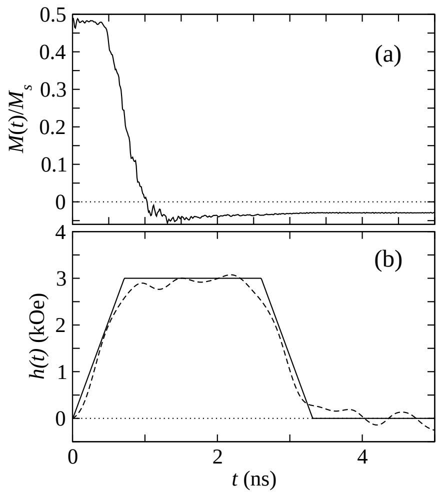

Figure 2: The magnetization response (a) as a function of time for a trapezoidal field pulse of half width 2.6ns (b). The dotted line in (b) shows a 2.6ns pulse generated by stripline experiment.

Gaussian distribution of the easy axes peaked along the z direction. Moreover, to make the system more realistic we have introduced a log-normal distribution of the anisotropy field and the exchange constant; the latter effectively takes into account a distribution of grain size in the system. That is, we take $H_K = H_K^0 \exp(\sigma_{H_K} x)$ and $A = A^0 \exp(\sigma_A x)$ where x is chosen from a Gaussian distribution of variance 1. The distribution of the anisotropy field is determined by two parameters, H_K^0, which is the median value, and the dimensionless width parameter σ_{H_K}, which is the rms variation in $\ln(H_K)$. Similarly the distribution of the exchange constant is determined by A^0 and σ_A. The best fit of the hard axis loop to the corresponding experimental loop, as shown in Fig. 1, was obtained with $H_K^0 = 9.2$ kOe with $\sigma_{H_K} = 0.02$, and $A^0 = 7 \times 10^{-12}$ J/m with $\sigma_A = 0.5$. The root-mean-square angular easy axis deviation used for the fit was 0.07 radians.

It is also important to look at the easy axis loop to make sure that the set of parameters used in the simulation provide the correct value of the remanent magnetization. Unlike the hard axis loop, however, the easy axis loop is highly sensitive to the field sweep rate because at slow sweep rates the loop is narrowed by thermally-activated grain reversals. Simulation is very time-consuming at slow rates, and the most important parameter is the remanent magnetization, so we did not simulate the entire easy axis loop – we determined the remanent magnetization M_{rs} by saturating the system along the z direction and subsequently letting it evolve in zero field. The demagnetizing field causes a few grains to flip and the system arrives at a metastable state in a few nanoseconds. The average value of $M_{rs} = 0.49 M_s$ obtained in our simulations was in excellent agreement with the experimental observation. Thus, it was possible

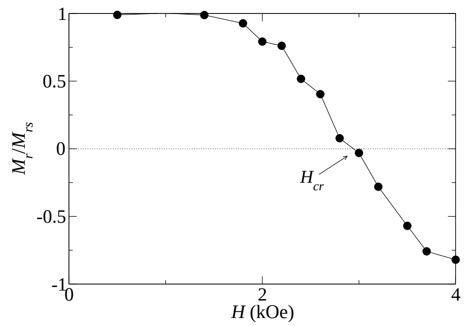

Figure 3: Remanent magnetization M_r/M_s as a function of the strength H of a 2.6ns pulse.

to tune the parameters and their respective dispersions to simultaneously fit the hard axis loop and give the correct remanent magnetization.

For the study of the effect of short pulses on our media at room temperature (300 K) we start with the system in its remanent state, and apply a reverse pulse (Fig. 2(b)). To find the remanent coercivity, we look at the system a long time after the pulse has ended and the system has reached a quasi-equilibrium state with magnetization $M_r = M(t = \infty)$. The remanent coercivity is defined as one that produces $M_r = 0$.

The pulses in a stripline experiment[8] are nearly trapezoidal, so we fit them to a trapezoid. The fall time has very little effect (there is almost no switching during the fall) so for simplicity we assumed it to be the same as the rise time. We take the duration of the pulse Δt to be the width at half maximum of the trapezoid.The magnetization response as a function of time t in a typical pulsed-field simulation is shown in Fig. 2. The animated visualizations [9] of our simulations show that there are a few 'switching nuclei', grains that are energetically unstable because their magnetostatic energy is increased by having a larger-than-average number of parallel neighbors. These particles are the first to switch when the external field is turned on. The switching process of these particles dumps energy to their neighbors making them unstable as well, triggering a chain reaction. Within a few hundred picoseconds the only remaining unswitched grains have low demagnetization fields, so the system is metastable.

Fig. 3 shows how M_r varies with the strength of a 2.6 ns pulse. This pulse length was chosen because it is the shortest pulse easily obtainable in a stripline experiment, and longer pulses are extremely time consuming to simulate. The remanent coercive field H_{cr} is defined as the field where the curve crosses zero. This curve is in qualitative agreement with preliminary experiments[8]; we hope to make a detailed comparison in a later communication.

It is important to look at how the coercive field varies with the pulse width. Fig. 4 shows how H_c increases with shorter pulses. The rather long rise time of 0.71 ns of the pulses sets a lower limit to the width of the pulses

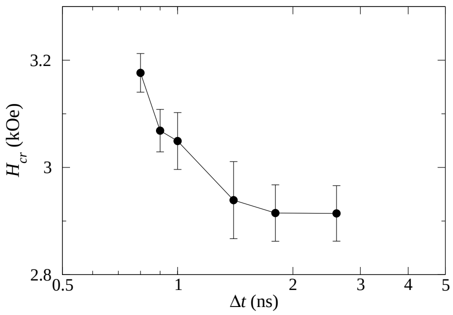

Figure 4: Coercive field as a function of the pulse duration.

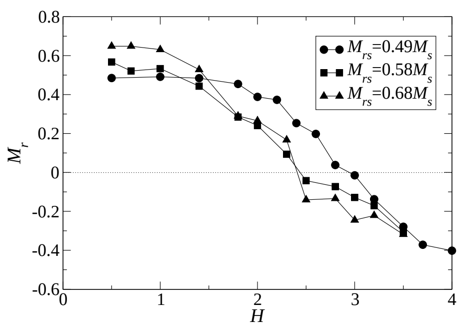

Figure 5: Effect of the initial remanent state on the coercive field. These remanent states were obtained by evolving an ensemble of saturated systems in zero field. The variation in M_r is caused by the finite size of the system.

that can be used; the shortest pulse in Fig. 4 is nearly of triangular shape. We have not used pulses longer than 2.6 ns in our simulation as most of the switching takes place in less than a nanosecond. We expect to see thermal switching in our system at longer time scales and a further logarithmic decrease of the remanent coercivity, but it would require much longer simulations to investigate such effects.

The demagnetizing field plays a crucial role in triggering the switching process. We have seen in our simulations that a system switches faster when the pulse is applied at a state with higher remanent magnetization. This counter intuitive behavior, which is also confirmed by experiments, is depicted in Fig. 5. The reason for such a behavior can be explained by noting that at a higher remanence state each particle is on the average surrounded by more particles aligned along the same direction. This increases the demagnetizing field felt by each particle and hence there are more switching nuclei in the system. Therefore, a relatively smaller external field can trigger switching in the system.

It would be useful to extend these calculations to times at which thermal switching is important, at which one expects the remanent coercivity to have logarithmic time dependence of Sharrock's Law[10]. This has been done in the context of Monte-Carlo simulation[11] and may be possible in a Landau-Lifshitz simulation by temperature-accelerated dynamics techniques.

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