Thermally induced magnetization reversal in antiferromagnetically coupled media

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The calculation of energy barriers between stable equilibrium states in strongly interacting systems requires the calculation of saddle points in high dimensional energy landscapes. We combine the nudged elastic band method with finite element micromagnetics to calculate optimal paths, giving a global view of thermal switching in antiferromagnetically coupled media. Energy barriers and transition rates can be estimated from the saddle points and the energy minima along this path. We investigate the dependence of the energy barrier on the strength of the antiferromagnetic coupling and study the reversal in the data bit transition region. Below 1.1 mJ/m^2 a two step reversal occurs passing a metastable state. Above 1.1 mJ/m^2 this metastable state disappears and the energy barrier is constant for a coupling strength greater than 1.5 mJ/m^2. [DOI: 10.1063/1.1558237]

I. INTRODUCTION

The thermal stability of magnetic media and magnetic storage elements becomes important with decreasing size of the magnetic structures. The calculation of the thermal stability requires the estimation of transition rates between stable equilibrium states of the magnet. The calculation of transition rates needs a detailed characterization of the energy landscape along the most probable path which is taken by the system from its initial state to a final state. Using the finite element method it is possible to represent complex geometries and grain structures. While it is straightforward to calculate energy minima a much more demanding task is to find the saddle points between the minima. Even for low dimensional models, e.g., a macrospin model for antiferromagnetically coupled (AFC) media where two spins are exchange coupled, this calculation[1] is quite complex although it has just four degrees of freedom. We combine the elastic band method with finite element micromagnetics to calculate the saddle points and energy barriers. The method is robust and allows models with many degrees of freedom. We start with one irregularly shaped AFC grain [Fig. 1(b)] meshed with about 800 nodes. In a next step energy barriers in the data bit transition region were calculated in a model with 19 irregularly shaped AFC grains [Fig. 1(a)] with a tetrahedral mesh of ~5000 nodes.

II. METHOD

To calculate optimal paths we follow the idea of Henkelman and Jónsson[2] and combine the nudged elastic band method with finite element micromagnetics.[3] In micromagnetics we represent the magnetic states of a system by a set of magnetic moments. This corresponds to the magnetization at the nodes of the finite element mesh, which is used to model the geometry of the magnet. A sequence of n magnetic states is constructed in such a way as to form a discrete representation of a path from the initial magnetization state $\mathbf{M}_i$ to the final magnetization state $\mathbf{M}_f$. The most simple case of the initial path is just a straight line with linear interpolation in the configuration space between $\mathbf{M}_i$ and $\mathbf{M}_f$. An iterative optimization algorithm is then applied until at any point along the path the gradient of the energy is only pointing along the path which also means that the path integral of the micromagnetic action along this path is in a local minimum.[4] Another expression for this optimal path is also ''minimum energy path,'' and means that the energy is stationary for any degree of freedom perpendicular to the path. A detailed description of the method as applied in micromagnetics is given elsewhere.[5]

III. RESULTS

AFC media is a prominent candidate where thermal stability is increased by a stabilizing layer.[6,7] The recording layer and the stabilizing layer are separated by a thin nonmagnetic Ru-spacer of about 0.8 nm thickness which couples the two layers antiferromagnetically. For an interface area of

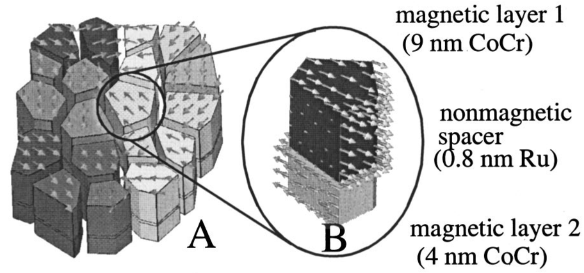

FIG. 1. (a) Data bit transition region in AFC media. (b) One grain of AFC media has reversed. The interface area of the enlarged AFC grain is 96.15 nm^2. V_1 and V_2 are the volumes of the top and bottom layer grains ($V_1 = 865$ nm^3, $V_2 = 385$ nm^3).

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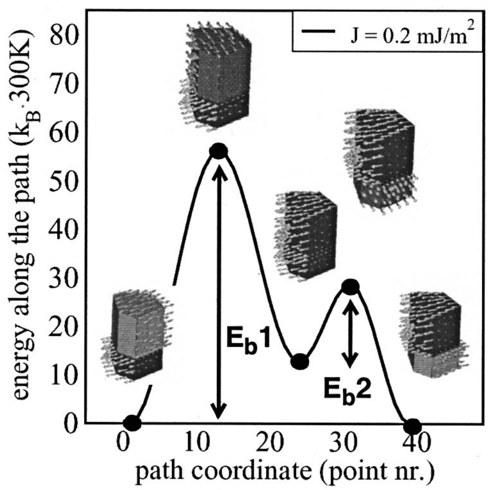

FIG. 2. Energy along the optimal path for an exchange coupling $J = 0.2\ \mathrm{mJ/m^2}$ ($J \times \mathrm{Area} \sim 4.8\ k_BT$). The magnetization reverses by a two step process passing two energy barriers. Energy barriers and magnetization states are indicated.

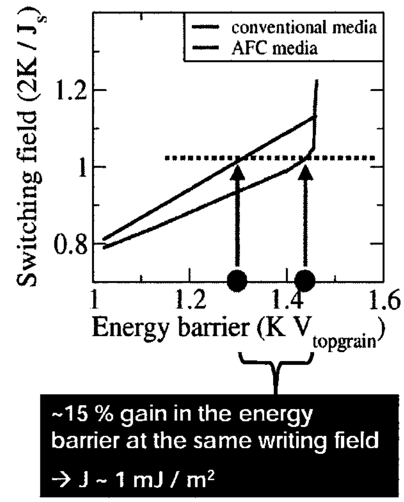

FIG. 4. Switching field as a function of the energy barrier. Compared are conventional media with AFC media. The reversing field is applied 21° to the easy axis. From the horizontal line we see that the energy barrier of the AFC media is 15% higher that the one of conventional media at the same switching (writing) field.

96.15 nm^2 and a coupling strength up to 5 mJ/m^2 this gives energies up to 48 k_BT. The uniaxial anisotropy energy is in the order of 50 k_BT.

We start by investigating the energy barrier dependence on the interface coupling strength for an isolated irregularly shaped AFC grain as shown in Fig. 1(b). As a basic set of parameters we choose the following values: $A_{\mathrm{bulk}} = 10$ pJ/m, $J_{s1} = J_{s2} = 0.375$ T and $K_{u1} = K_{u2} = 2.30$ kJ/m^3. For weak coupling ($J < 1.1$ mJ/m^2) a two step reversal occurs. First one layer reverses and the system remains in a metastable state where both grains are parallel until the second layer switches. The two step reversal mode is shown in Fig. 2. The energy barrier increases linearly with the coupling strength reaching 1.41 K_uV_1 at about 1 mJ/m^2. K_u is the uniaxial anisotropy and V_1 and V_2 are the volumes of the two subunits [see Fig. 1(b)]. Above a critical coupling strength of 1.1 mJ/m^2 the metastable state disappears (see Fig. 3). Above this critical value the interface coupling energy exceeds the energy for uniform rotation of the smaller grain. For thinner bottom layers a smaller coupling strength is sufficient to reach this critical point. The energy barrier

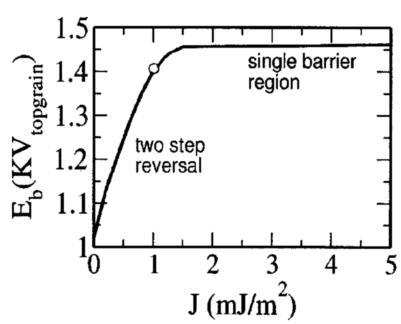

FIG. 3. Energy barrier as a function of the interface coupling strength for one isolated AFC grain. The point indicates the critical coupling strength which separates the two- and the one-step reversal mode. V_1 and V_2 are the volumes of the top and bottom layer grains ($K = 230$ kJ/m^3, $V_1 = 865$ nm^3, $V_2 = 385$ nm^3).

still increases with the coupling strength reaching 1.45 K_uV_1, at $J \sim 2$ mJ/m^2. Above this value saturation is reached (Fig. 3).

For a high quality recording media a high energy barrier alone is not sufficient. This could be achieved by just increasing the anisotropy in conventional media. The second important quality factor is the writability of the media since the recording head has only a limited writing field. The desired "good writability" media should have a low switching field but keep a high energy barrier. In a second step we calculate the switching fields using standard dynamic micromagnetics[8] using a value of 0.02 for the Gilbert damping constant. The reversing field is applied in plane under an angle of 21° (Ref. 9) to the easy axis of the grain. The results are shown in Fig. 4. We compare the switching field H_c of conventional media with AFC media as a function of the corresponding energy barrier. In the case of conventional media (using the top layer grain only of our AFC model) we increased the energy barrier by varying (increasing) the anisotropy constant K_u (starting from 230 kJ/m^3). In AFC media the energy barrier is increased by varying (increasing) the interface coupling strength but keeping the anisotropy constant ($K_u = 230$ kJ/m^3). The dashed line shows that the energy barrier is increased by 15% as compared to conventional media without increasing the switching field H_c. This best gain corresponds to an interface coupling strength in the AFC media where the reversal mode changes from two step to one step reversal (see Fig. 3). Here the interface coupling energy is about 110% of the anisotropy energy of the bottom layer/grain.

The method also allows the calculation of more complex models. We constructed a model of 19 irregularly shaped AFC grains. The average grain diameter was 9 nm and with 0.9-nm-thick nonmagnetic grain boundaries in between. The top and bottom layer had equal parameters as in the example of the single grain. The energy barrier was calculated for a grain in the data bit transition region as shown in Fig. 1(a). Although the model is complex and the dimension of the discretization space high the method gives the proper saddle point and corresponding energy barrier in a reasonable computing time (1/2 day, when meshed with 5000 nodes) on a single processor desktop computer. The calculated energy barriers differ only slightly from the energy barrier of the isolated grain and is about 3% smaller. This is explained by the demagnetizing field in this region.

IV. SUMMARY

The elastic band method was used to calculate optimal paths, saddle points, and energy barriers of antiferromagnetically coupled media. The stabilizing layer increases the energy barrier by 15% as compared to conventional media without increasing the switching field. The method is capable of calculating energy barriers of grains within the bit transition region. Here demagnetizing fields lower the energy barrier by 3% as compared to the case of one isolated AFC grain.

[1] H. J. Richter and Er. Girt, IEEE Trans. Magn. **37**, 1441 (2001).
[2] G. Henkelman and H. Jónsson, J. Chem. Phys. **113**, 9978 (2000).
[3] D. R. Fredkin and T. R. Koehler, IEEE Trans. Magn. **24**, 2362 (1988).
[4] D. V. Berkov, J. Magn. Magn. Mater. **186**, 199 (1998).
[5] R. Dittrich, T. Schrefl, D. Suess, W. Scholz, H. Forster, and J. Fidler, J. Magn. Magn. Mater. **250**, L12 (2002).
[6] L. Guan and J. G. Zhu, J. Appl. Phys. **91**, 7688 (2002).
[7] A. Inomata, B. R. Acharya, E. N. Abarra, A. Ajan, D. Hasegawa, and I. Okamoto, J. Appl. Phys. **91**, 7671 (2002).
[8] D. Suess, V. Tsiantos, T. Schrefl, J. Fidler, W. Scholz, H. Forster, R. Dittrich, and J. J. Miles, J. Magn. Magn. Mater. **248**, 298 (2002).
[9] H. J. Richter, IEEE Trans. Magn. **35**, 2790 (1999).