Thermal relaxation in antiferromagnetically coupled granular magnetic media

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Using a conventional recording system we have characterized the thermally activated transition formation process in the lower layer of antiferromagnetically coupled magnetic recording media. We find that this thermal relaxation time depends strongly on the transition density, lower layer alloy composition, and layer thickness. A one-dimensional analytic model of coupled granular media that includes interlayer exchange, intergranular exchange, and magnetostatic energies is able to reproduce the observed results.

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Antiferromagnetic exchange coupling between two magnetic layers separated by a thin Cr layer was discovered in 1986.[1] Recently, longitudinal recording media based upon this effect was proposed[2,3] to improve thermal stability of recorded information and to overcome superparamagnetic effects, which limit the traditional scaling of recording media parameters.[4] This antiferromagnetically coupled (AFC) media structure consists of a thinner ferromagnetic lower layer (LL), which is antiferromagnetically coupled through a thin nonmagnetic Ru layer to a thicker upper layer (UL). The ferromagnetic media layers have a granular microstructure where the grains are magnetic and the grain boundaries are weakly magnetic or nonmagnetic. In the antiferromagnetic (AF) state, the effective magnetic thickness $M_r t_{\mathrm{eff}}$ of the composite structure is given by the difference between the $M_r t$ of the two layers where M_r is the remanent magnetization and t is the thickness of the layers. This configuration allows the optimization of the magnetic thickness $M_r t_{\mathrm{eff}}$ independently of the physical thickness of the recording medium t, while only marginally increasing the write field requirement. AFC media behave magnetically similar to a thin single-layer media in recording experiments, while thermal stability is improved as a result of the thicker UL (Ref. 5) and the AF exchange coupling (Refs. 6–8).

One consequence of the AFC media structure is the increased complexity of the write process as compared to traditional single-layer media. The final magnetic configuration is achieved by the thermally activated reversal of the LL. In the present manuscript we explore the transition formation process in the LL, which allows studying the interplay among AF coupling strength, UL transition density, and LL material properties such as thickness and intergranular exchange. This provides a model system for investigating the complex physics of the interactions between granular magnetic thin films at controlled length scales. The experimental data are analyzed using a one-dimensional model.

The write process in AFC media may be described by two phases. In the initial phase, while the magnetic field of the write head is present, the UL and the LL are magnetized parallel to the applied field direction. After the head field is removed the LL reverses and becomes antiparallel to the UL. In this process transitions are formed in the LL, which have opposite polarity to the transitions that are recorded in the UL (i.e., the transitions in the LL are not written by the head field). Thermal activation plays an important role in this process. Antiparallel alignment of UL and LL is experimentally observed, even though the intrinsic switching field of the LL is larger than the interlayer exchange field.[9,10] That is, the AF exchange is not sufficient to reverse the LL in the absence of thermal activation. The speed of this relaxation process and the magnetization state, which the LL assumes in thermal equilibrium, are of paramount importance to the recording performance such as media noise, read-back signal, and thermally activated signal decay.

In the present experiments the dependence of the relaxation process of the LL in the presence of transitions in the UL is characterized using a novel spin-stand recording technique. In particular, the dependence on the LL thickness, intergranular exchange coupling, and AF exchange coupling on the relaxation time are explored. Three different media series are investigated. The UL's are equal in all media samples and consist of a Co-Cr-Pt-B alloy with an $M_r t$ of 0.38 memu/cm^2. The $M_r t$ of the LL is varied for each series between 0.13 and 0.23 memu/cm^2 by varying the thickness of the layer t. The LL's are CoCr-based alloys where the composition is chosen such that the LL write field is much smaller than that of the UL. The LL of sample series A and C have a higher Co content, and as a result, a high intergranular exchange. Intergranular exchange and M_r in the LL are reduced in sample series B by increasing the Cr content of the alloy. Note that in order to achieve the same LL $M_r t$ the LL's are thicker in sample series B than in A and C. The AF exchange coupling is maximized for sample series A and B employing a 0.6-nm-thick Ru layer and essentially vanishes for series C with a 1.2-nm-thick Ru layer.[10]

The experiments are performed on a Guzik spin stand. Transitions are first written into the recording medium using a high write current at densities ranging from 0 to 23.7 kfc/mm (kilo-flux-changes per millimeter). Then transitions are written into the LL at a fixed linear density of 3.94 kfc/mm using a low write current resulting in a bit spacing d_{LL} of 254 nm. The final magnetic configuration is shown schematically in Fig. 1(a). This second write process does not influence the magnetization state of the UL, which has a much higher coercive field and was verified for AFC media with a very thin LL. Finally, ~2 s later the LL signal amplitude is determined using the read head. This procedure is repeated for each UL linear densities on the three series of samples. Figure 1(c) shows a typical frequency spectrum of the read back signal resulting from this procedure. The ar-

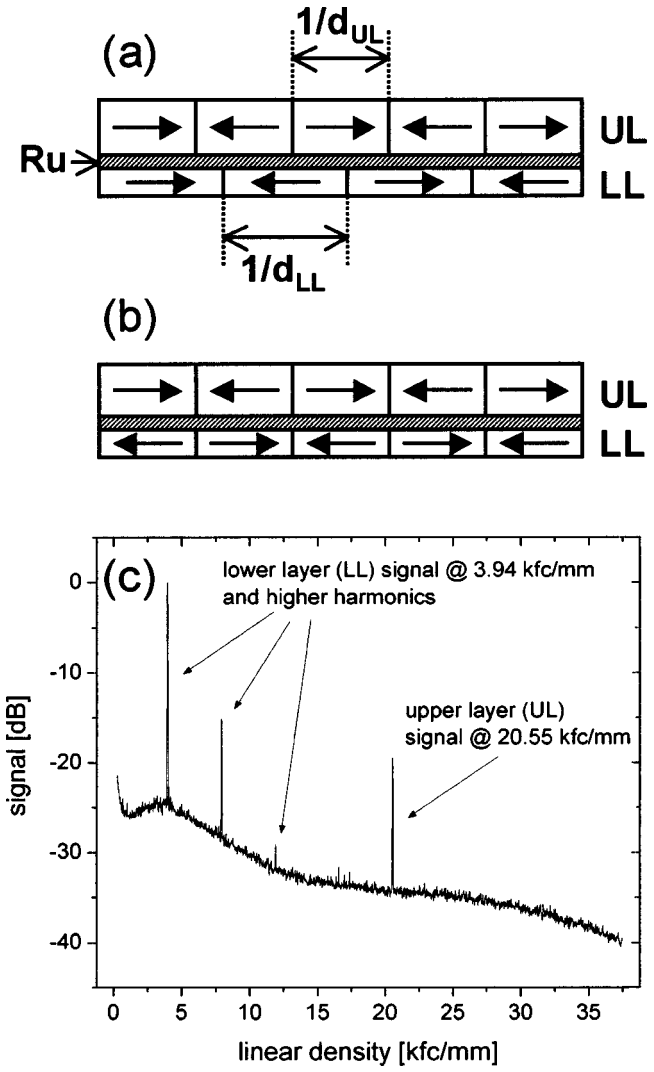

FIG. 1. (a) Transition positions after the lower layer write process showing different densities in the upper layer and lower layer. (b) Transition positions after complete thermal relaxation. (c) Frequency spectrum of a track after the write process [see (a)], where the upper layer is written at 20.55 kfc/mm and the lower layer at 3.94 kfc/mm.

rows in the figure point to the signal peaks at 20.55 kfc/mm for the UL and 3.94 kfc/mm for the LL. Additionally, the frequency spectrum also shows peaks at higher harmonics of the LL signal.

Immediately after the second write process, the LL magnetization is in a well-defined state with a transition every ~254 nm. The LL transitions and consequently also the LL signal amplitude are almost independent of the transitions in the UL. As time progresses, however, the LL relaxes towards its thermal equilibrium configuration with the same magnetic periodicity of the UL [Fig. 1(b)]. That is, the transitions, which were written into the LL at a linear density of 3.94 kfc/mm, disappear and new transitions conforming to the transitions in the UL are formed. The LL signal amplitude at 3.94 kfc/mm reflects the status of this relaxation. If the LL signal amplitude is large, only limited relaxation took place by the time the signal amplitude measurement was performed and the relaxation time is long. In contrast, if the LL signal amplitude vanishes, the LL relaxed into a thermal equilibrium, indicating a short relaxation time. Since the relaxation time is intimately related to the energy barrier for magnetization reversal $E_B = K_u V$,[11] where K_u is the anisotropy energy and V is the volume of a magnetic grain in the LL, one can deduce relative energy barrier heights from the signal amplitude measurements. This simplified decay measurement works, because relaxation times are short compared to the UL as a result of the small energy barriers in the thinner LL. Note that since the linear density of the signal of interest is kept constant, the density dependence of the read head response is eliminated.

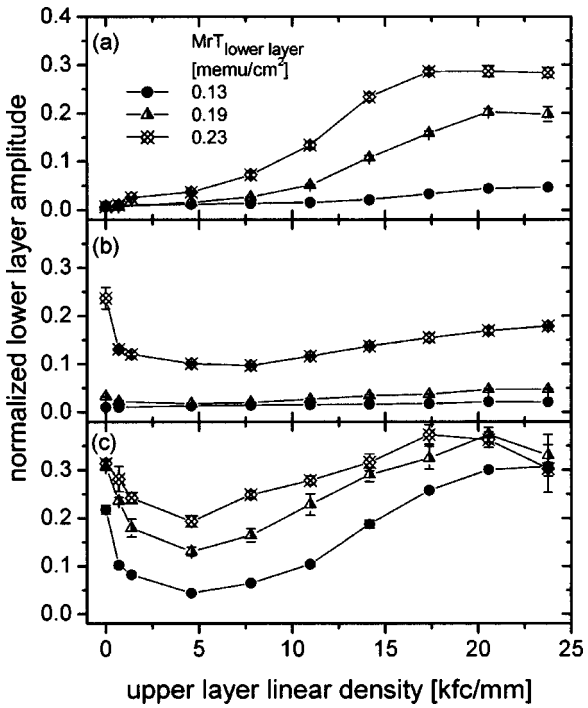

FIG. 2. Lower layer amplitude at 3.94 kfc/mm 2 s after writing the lower layer as a function of the upper layer linear density. (a) The lower layers have high Co content and high intergranular exchange coupling (sample series A). (b) The lower layers have reduced Co content and reduced intergranular exchange coupling (sample series B). (c) The lower layer is the same as in (a), but the antiferromagnetic exchange coupling is reduced using a 1.2-nm-thick Ru layer (sample series C).

Plotted in Fig. 2(a) is the LL signal amplitude as a function of the UL linear transition density for sample series *A* (high Co content, high intergranular exchange) for three different LL $M_r t$ values. The plotted signal amplitudes are normalized by the LL $M_r t$. All three samples show a similar dependence. When the UL is in dc-erased state (no transitions are present), no LL signal is detected in the amplitude measurement, i.e., the LL has already relaxed into its thermal equilibrium state within 2 s. As the UL linear density is increased, the signal amplitude of the LL also increases, indicating that the LL relaxation time increases. Furthermore, we observe that relaxation times also increase as the LL becomes thicker. The latter results are a direct consequence of the larger intrinsic energy barrier $E_B = K_u V$ for thicker LL.

Assuming cylindrical grains whose diameter is independent of film thickness, we find that E_B increases linearly with film thickness. This trend is observed for all three sample series (Fig. 2).

When the Cr content in the LL is increased [Fig. 2(b)] or when the AF coupling is reduced [Fig. 2(c)], the amplitude curves as a function of transition density assume a different shape. At both low and high UL transition densities, LL signal amplitudes are high and a minimum is observed at a medium UL transition density between 4 and 8 kfc/mm.

In order to model this surprisingly complex behavior, we consider the magnetic energy of the system assuming that the UL does not change its magnetization state during the relaxation of the LL. Then, in thermal equilibrium the average magnetic energy associated with the LL, $E_{\mathrm{tot}}^{\mathrm{equi}}(d_{\mathrm{UL}},d_{\mathrm{LL}})$, for one bit cell is given by the interlayer exchange, magnetostatic, and and intergranular exchange energies:

$$E_{\mathrm{tot}}^{\mathrm{equi}}(d_{\mathrm{UL}},d_{\mathrm{LL}})=E^{\mathrm{AF}}(d_{\mathrm{UI}},d_{\mathrm{LL}})+E_{\mathrm{UL}}^{\mathrm{ms}}(d_{\mathrm{LL}})+E_{\mathrm{LL}}^{\mathrm{ms}}(d_{\mathrm{UL}})+E_{\mathrm{LL}}^{\mathrm{ms}}(d_{\mathrm{LL}})+E_{\mathrm{LL}}^{\mathrm{ex}}(d_{\mathrm{LL}}), \quad (1)$$

where d_{UL} and d_{LL} are the transition densities of the UL and LL, respectively.

$$E^{\mathrm{AF}}(d_{\mathrm{UL}},d_{\mathrm{LL}})=-J_{\mathrm{AF}}W\int_{-B/2}^{B/2}m_{\mathrm{UL}}m_{\mathrm{LL}}dx. \quad (2)$$

is the AF exchange energy, where m represents the normalized magnetization, $B=1/d$, is the bit length, W is the track width, and J_{AF} is the AF exchange coupling energy density. If intergranular exchange coupling in the LL is present, the AF exchange energy is averaged over some grains, effectively leading to a reduction of the AF exchange energy. This reduction is particularly large close to transitions, where the UL magnetization changes rapidly across the transition and the average magnetization approaches zero. As a consequence, the AF exchange energy gain is density dependent and becomes smaller at high transition densities. Therefore Eq. (2) provides a lower estimate for the AF exchange energy for high LL intergranular exchange. In contrast, if no or negligible intergranular exchange energy is present in the LL, the magnetization of each LL grain aligns itself antiparallel to the UL. In this case, the AF exchange energy is independent of the UL transition density and may be estimated by

$$E^{\mathrm{AF}}=-J_{\mathrm{AF}}WB. \quad (3)$$

The magnetostatic energies arising from the transitions in the magnetization are given by

$$E_{xL}^{\mathrm{ms}}(d_{yL})=-t_{xL}W\int_{-B/2}^{B/2}H_{yL}^{\mathrm{demag}}M_{xL}dx, \quad (4)$$

where H_{yL}^{demag} is the demagnetization field generated by layer yL acting on layer xL with the magnetization M_{xL} ($xL,yL=\mathrm{UL,LL}$), and t_{LL} the LL thickness. Finally, the intergranular exchange energy in the LL is calculated by

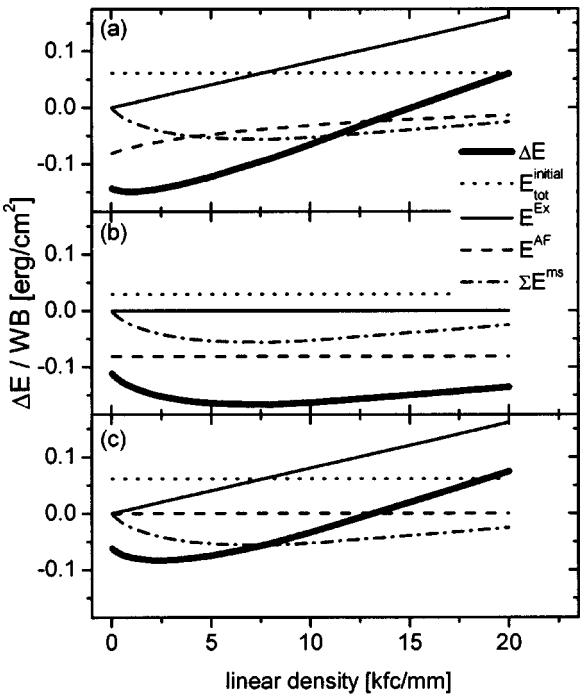

FIG. 3. Calculation of the energy gains (total and split up into the individual contributions) as a result the formation of transitions in the lower layer as a function of linear density. Case (a) is for a lower layer with intergranular exchange coupling, case (b) without intergranular exchange coupling, and case (c) without antiferromagnetic exchange coupling between the magnetic layers.

$$E_{\mathrm{LL}}^{\mathrm{ex}}(d_{\mathrm{LL}})=J_{\mathrm{ex}}t_{\mathrm{LL}}W\int_{-B/2}^{B/2}[\nabla m_{\mathrm{LL}}(d_{\mathrm{LL}})]^2dx, \quad (5)$$

where J_{ex} is the intergranular exchange energy density. In order to simulate the granularity of the medium, an 8-nm step size is chosen for the integration in $E_{\mathrm{LL}}^{\mathrm{ex}}(d_{\mathrm{LL}})$.

Immediately after the write process, the positions of the transitions in the UL and LL are uncorrelated, and

$$E_{\mathrm{UL}}^{\mathrm{ms}}(d_{\mathrm{LL}})=E_{\mathrm{LL}}^{\mathrm{ms}}(d_{\mathrm{UL}})=E^{\mathrm{AF}}(d_{\mathrm{UL}},d_{\mathrm{LL}})=0. \quad (6)$$

It follows from Eq. (1) that $E_{\mathrm{tot}}^{\mathrm{initial}}(d_{\mathrm{UL}},d_{\mathrm{LL}})=E_{\mathrm{LL}}^{\mathrm{ms}}(d_{\mathrm{LL}})+E_{\mathrm{LL}}^{\mathrm{ex}}(d_{\mathrm{LL}})=\mathrm{const}$, since $d_{\mathrm{LL}}=3.94$ kfc/mm$=$const. The energy gain resulting from thermal relaxation in the LL can then be easily calculated using

$$\Delta E=E_{\mathrm{tot}}^{\mathrm{equi}}(d_{\mathrm{UL}},d_{\mathrm{LL}})-E_{\mathrm{tot}}^{\mathrm{initial}}(d_{\mathrm{UL}},d_{\mathrm{LL}}). \quad (7)$$

ΔE is directly related to the relaxation time, as the total energy barrier for magnetization reversal to first order is proportional to ΔE.

Figure 3 shows three calculations of the total energy gain and the individual contributions from magnetostatic and AF interactions, and intergranular exchange energy as a function of density, corresponding to the sample series A–C. Here, the energy gain is normalized to the surface area of the tracks $\Delta E/WB$. The AF exchange energy $J_{\mathrm{AF}}=-0.06$ erg/cm^2 is estimated from minor loops. Figure 3(a) shows the calculated energy gain for sample series A, which has high Co content and high intergranular exchange. The intergranular exchange

$J_{ex}=0.17$ μerg/cm is estimated from parametric spin-stand measurements using the present model.[12] The AF exchange energy is calculated using Eq. (2) and is dominating at low transition densities. The density dependence, however, is dominated by the intergranular exchange energy and agrees well with the experimental findings in Fig. 2(a).

The energy gain for sample series B is shown in Fig. 3(b), using the same parameters as in Fig. 3(a), except $J_{ex}=0$, leading to a density independent E^{AF} [Eq. (3)]. Here, at low transition densities the density dependence of the magnetostatic energy gain dominates the functional form of $\Delta E/WB$, while the relaxation at high transition densities is determined by the reduction in the AF exchange and magnetostatic energy gain. Again, good agreement with the experiment is observed [Fig. 2(b)]. Performing the same calculation for sample series C, where J_{AF} vanishes and $J_{ex}=0.17$ μerg/cm, we find that the energy gain at low densities is much smaller than in the other two examples, and the relaxation time is long [Fig. 3(c)]. At medium and high transition densities, the system is dominated by the interplay between intergranular exchange and magnetostatic energy gains, in good agreement with the experiment.

In conclusion, the interactions between two antiferromagnetically coupled granular layers have been investigated by characterizing the thermal relaxation of one layer in the presence of transitions in the other layer. Results were presented on the relaxation of the lower layer in antiferromagnetically coupled media and analyzed using a one-dimensional analytical model. We find that—in addition to the stability ratio of the lower layer and the antiferromagnetic exchange coupling—intergranular exchange also plays an important role for the thermal relaxation of the lower layer after the write process. In particular, when writing at high transition densities, the presence of intergranular exchange in the lower layer can significantly slow the thermal relaxation process. The complexity of the observed behavior arises from the fact that the involved energies are similar in size, and the dominating type of energy may change depending on transition density, antiferromagnetic exchange coupling, and lower layer alloy composition.

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