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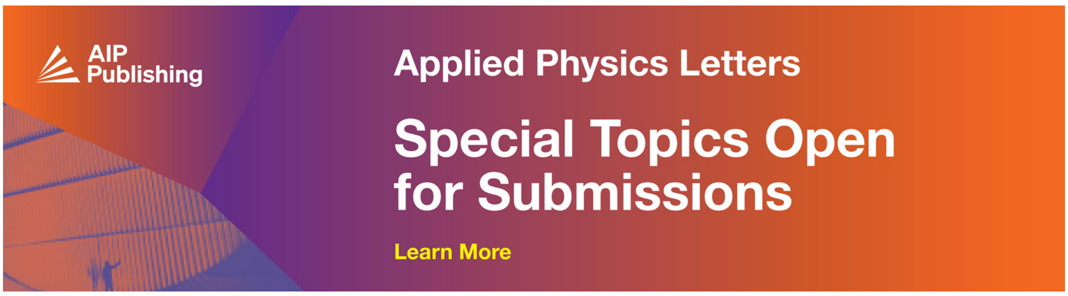

Exchange spring media for perpendicular recording

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A novel type of exchange spring media is proposed for magnetic recording systems consisting of a hard/soft bilayer. Finite element micromagnetic simulations show that the reversal modes induced by the external write field are significantly different from the thermally activated switching processes. Thus, the bilayers can be optimized in order to achieve a high thermal stability without increase of coercive field. In grains with identical size and coercivity an optimized bilayer reaches an energy barrier exceeding those of optimized single phase media by more than a factor of two. Additionally the lower angular dependence of coercivity of exchange spring media will improve the signal to noise ratio. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1951053]

Further increase of areal density in magnetic recording is believed to be limited by the superparamagnetic limit, as thermal fluctuations at room temperature ($k_B T_{300}$) may overcome the energy barrier ($\Delta E = KV$) separating both magnetization directions of an isolated grain with a volume V and an uniaxial anisotropy constant K. According to the Stoner–Wohlfarth theory (SW) an increase of anisotropy may compensate for the required decrease of grain size, but results in an unfavorable increase of coercivity $\mu_0 H_c$. The maximum fields achievable with perpendicular writing head are limited by to about 1.7 T.[1] The coercive field of a single domain particle can be decreased by 20% to 40% while keeping the energy barrier constant by using magnetic materials with a combined anisotropy (cubic and uniaxial) as shows by Usov *et al.*[2] An other possibility to overcome the writing problem is to employ thermally assisted recording.[3] Thiele *et al.*[4] suggested to lower the coercive field by the use of FePt/FeRh bilayer system. Recently magnetic multilayer structures being composed of magnetically hard and magnetically soft layers were proposed, in order to address the recording problem.[5,6] In the model of Shen and Victora, the soft and the hard part of each grain remain uniform. In order to decrease the coercive field, the exchange coupling between these layers has to be reduced.

In this letter, exchange spring media are proposed which can be optimized for both, high thermal stability and low coercivity. This differs significantly from the scope of pioneering work on exchange spring systems, aiming at an optimization of energy product of bulk permanent magnets[7] and thin films.[8] In all calculations, coercivity was fixed at 1.7 T and, if not stated otherwise, the grain size of cylindrical grains was fixed at the dimensions expected for the next media generation (diameter 6 nm, thickness 14 nm). After presenting an analytical model for single phase media for comparison, micromagnetic calculations are used to analyze domain reversal in bilayers.

First, a simple analytical model for the optimization of a single phase data layer is given. With a given head field, one has to optimize the data layer properties such as K and J_s. When assuming that the film is composed of weakly coupled single domain grains, the energy barrier for a single domain particle is given by

$$\Delta E = KV(1 - H/H_{SW})^2, \tag{1}$$

where V is the volume of the grain and H is the effective field acting on the grain acting parallel to the easy axis. K is the effective anisotropy, which is the sum of the uniaxial anisotropy K_1 and the shape anisotropy. For a particle with the ratio length/diameter=2.5 and a polarization of 0.4 T, the shape anisotropy is $K_s = 3.7 \times 10^4$.[9] The SW switching field is given by $H_{SW} = 2K/J_s$. The effective field H is composed of the demagnetizing field and the exchange field from the neighboring grains. It acts parallel to the easy axis. The worst case for thermal stability is when all neighboring grains are magnetized parallel, described by a demagnetizing factor of 1. However, the exchange field from the neighboring grains stabilizes the grain, opposing the demagnetizing field. The effective field can be written as $H = J_s/\mu_0 - B_{ex}/\mu_0$. Here, J_s/μ_0 is the demagnetizing field and B_{ex} is the exchange field in Tesla. The maximum value of the anisotropy is limited by the maximum head field, B_h. The head field has to be large enough in order to saturate the film. Assuming all grains except one to be reversed, the switching field of the last grain (also called saturation field or closer field) can be expressed as $H_{SW,last} = 2K/J_s - B_{ex}\mu_0 + J_s/\mu_0$. The exchange field of the neighboring grains supports the switching of the last grain, whereas the demagnetizing field of the film hinders the

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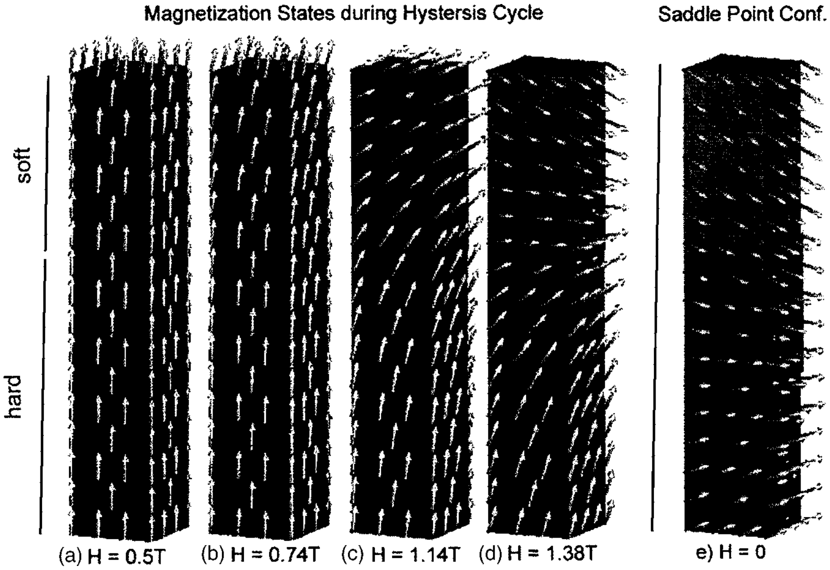

FIG. 1. Side view of a bilayer for perpendicular recording. (a)–(d) Magnetization states during the hysteresis cycle for the bilayer with $J_{s,\mathrm{hard}}=0.26$ T and $J_{s,\mathrm{soft}}=0.9$ T. Configuration (a) shows the remanent state for the fully magnetizated disk. (e) Here, the saddle point configuration without external field is shown. This configuration requires the lowest thermal activation energy for domain reversal.

switching of the last grain. The minimum head field to record on the data layer is $B_h=\mu_0 2K/J_s-B_{\mathrm{ex}}+J_s$. From this expression, K can be expressed as a function of J_s, B_{ex}, and B_h and substituted in Eq. (1). By setting the first derivative of Eq. (1) with respect to K to zero, the optimum value follows from an equation of third order. Thus, we obtain values for K and J_s that maximize the energy barrier for a given head field.

The solution of interest is given by

$$K=\frac{1}{32\mu_0}(3B_h+3B_{\mathrm{ex}}-\gamma)(B_h+B_{\mathrm{ex}}+\gamma)$$

with $\gamma=\sqrt{5B_h^2+6B_hB_{\mathrm{ex}}+B_{\mathrm{ex}}^2}$. The optimum value of the magnetic polarization is given by $J_s=1/4(3B_h+3B_{\mathrm{ex}}-\gamma)$ and the energy barrier can be expressed as

$$\Delta E(B_h,B_{\mathrm{ex}})=V\frac{(3B_h+3B_{\mathrm{ex}}-\gamma)(-B_h+B_{\mathrm{ex}}+\gamma)^2}{8\mu_0(B_h+B_{\mathrm{ex}}+\gamma)}$$

. For each set of B_h and B_{ex}, the chosen values of K and J_s maximize the energy barrier. A contour plot of the energy barrier as a function of the head field and the exchange field shows that, in a first approximation, the isolines within the range of interest ($1\ \mathrm{T}<B_h<2\ \mathrm{T}$ and $0<B_{\mathrm{ex}}<0.5\ \mathrm{T}$) are parallel and straight lines. The energy barrier is almost constant for equal values of $b=B_{\mathrm{ex}}+0.36B_h$. Therefore, it can be approximated to be a function of just one variable, $\Delta E(B_h,B_{\mathrm{ex}})\approx\Delta\tilde{E}(b)$.

The finite element method was used to optimize the magnetic properties of an exchange coupled bilayer composed of a magnetically hard and soft layer for perpendicular magnetic recording. In the limit of vanishing soft magnetic layer thickness, the numerical results can be compared with the analytic model. The thickness of the hard layer and the thickness of the soft layer are changed. Furthermore, the values of K in the hard layer ($K_{\mathrm{soft}}=0$) and J_s—which is assumed as equal in the both layers—are varied.

For each configuration, the value of the anisotropy in the hard magnetic layer was changed iteratively in order to obtain a saturation field of the bilayer structure equally to the maximum possible head field of $B_h=1.7$ T. Instead of using Eq. (1), we calculate the energy barrier numerically using the nudged elastic band method.[10] For the calculation of the energy barrier both, the demagnetizing field and the exchange field are taken into account with an effective field, $H=J_s/\mu_0-B_{\mathrm{ex}}/\mu_0$. This effective field acts like an external field during the calculation of the saddle point configuration and saddle point energy. For each hysteresis loop calculation, the Landau–Lifshitz equation is integrated numerically while the external field is subsequently decreased. The demagnetizing field is taken into account via a reduction of the external field by J_s/μ_0. The exchange field helps to reverse the last grain of a bit. Therefore, it is added to the external field.

The soft layer which is fully exchange coupled to the hard layer acts as a magnetic spring that initiates the reversal of the hard layer similar to what is observed in composite permanent magnets.[1] A magnetic domain wall is created next to the hard/soft interface. Compared to a single phase media with the magnetic properties of the hard layer the coercive field is significantly reduced (by a factor of 6). The numerical results show two distinct reversal modes for switching by an external field and for switching caused by thermal fluctuations. These reversal modes are compared in Fig. 1 for a single grain of an exchange spring recording media. The thickness of the hard layer ($A=1\times10^{-11}$ J/m, $K=9.6\times10^5$ J/m^3, $J_s=0.26$ T) and the soft layer ($A=1\times10^{-11}$ J/m, $K=0$, $J_s=0.9$ T) is 8.7 nm and 5.3 nm, respectively. Figures 1(a)–1(d) show the reversal of the grain under the influence of an external field. Figure 1(a) shows the remanent state of of grain of the fully saturated film. As the external field reaches coercivity, the domain wall formed at the hard/soft interface propagates into the hard magnetic part. For zero-external field, thermal activations help the system to cross the energy barrier. Figure 1(e) depicts the magnetization distribution at the saddle point (An effective field of 0.2 T that represents the demagnetizing field and the exchange field is taken into account for the calculation of the energy barrier). This quasi-uniform state is most probably chosen by thermal activated reversal [Fig. 1(e)] and differs significantly from the reversal mode under the application of the switching field [Fig. 1(d)].

Due to different reversal mechanisms the ratio r between the energy barrier and the coercive field is not constant, as predicted by the SW theory,but allows an independent optimization by changing media properties. First, we investigate the influence of the fraction of the hard layer thickness to the

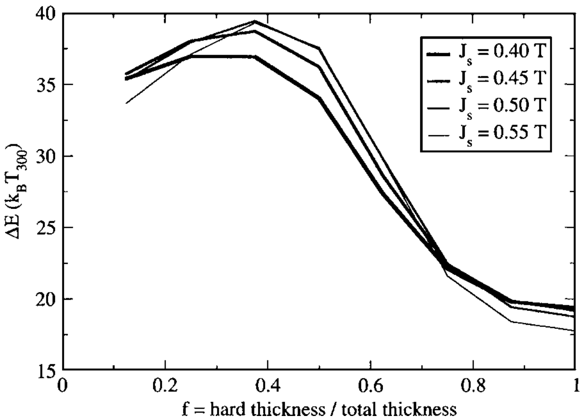

FIG. 2. Energy barrier as a function of the fraction of the hard layer thickness to the total thickness for a magnetic bilayer structure. Different curves are for different magnetic polarization which are set to be the identical for the hard magnetic and soft magnetic layer.

total thickness ($f=\ell_{\text{hard}}/\ell_{\text{total}}$) on the energy barrier, where $f=1$ describes a medium consisting of one complete hard magnetic layer. An exchange field of 0.2 T was assumed in the calculation. This is about 12% of the coercive field. First, both layers are set to an identical saturation polarisation ($J_s=J_{s,\text{hard}}=J_{s,\text{soft}}$). Figure 2 shows the calculated energy barrier as a function of f. Under the constrain of a saturation field of 1.7 T, the highest-energy barrier is obtained for $f=0.375$ and for $J_s=0.5$ T. The energy barrier of this optimal bilayer is more than two times larger than that of the single phase medium. The influence of J_s on the energy barrier for different film architectures is given in Fig. 3. For a single layer, the finite element simulations results in an energy barriers with a maximum at $J_s=0.42$ T, in excellent agreement with the analytic model predicting $J_s=0.41$ T.

As a second step, different values of J_s for the hard and soft layer are used. The optimal bilayer is found for the magnetic properties listed in the caption Fig. 1(a). The energy barrier increases to 48 k_BT_{300}—compared to 19 k_BT_{300} for the optimum single phase media. The influence of an exchange breaking layer between the soft and the hard layer on the energy barrier was investigated for $J_{s,\text{hard}}=J_{s,\text{soft}}=0.5$ T for different values of the fraction f. In a 1 nm thick spacer layer separating the hard and soft layer, the exchange constant was reduced by a factor of 2, 3, 4, 5, and 6. The results show that for all those values, the energy barrier decreases.

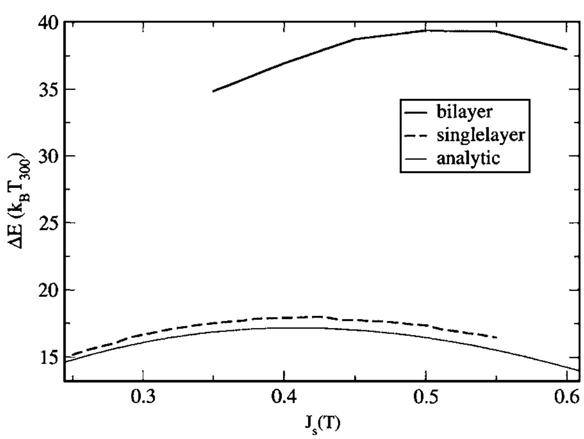

FIG. 3. Energy barrier as a function of J_s for the single layer and the bilayer. In the bilayer, the same value of J_s is taken in the hard and soft part.

A small angular dependence of the coercive field is important in order to obtain a high signal to noise ratio.[11] For the composite media, the angular dependence of the coercive field can be fitted with the expression $H_c(\alpha)=H_c(0)/\cos(\alpha)$. This expression is commonly used for magnetic materials which are controlled by domain-wall pinning. For an angle α between 0° and 40°, the deviation of the analytic formula and the finite element calculation are less than 5%. In contrast to exchange spring media, single phase media exhibit a strong angular dependence of the coercive field (described by the SW theory). For a misalignment of 10° between the external field and the easy axis, the coercive field increases by a factor of 1.01 for the composite media, whereas it decreases by a factor of 0.68 for the single phase media.

In conclusion, it was shown that exchange spring media can improve thermal stability by a factor of 2 compared to single phase media allowing at constant coercivity. The different magnetization state during switching in the head field compared to thermal switching allows one to optimize thermal stability and coercivity mostly independent from each other, resulting in a significant reduction of the stable grain size. Recent experiments by Okamoto *et al.*[12] showed that these properties indeed can be optimized independently. They prepared epitaxial FePt $L1_0$ nanoparticles covered with different Pt overlayer thicknesses. They observe a decrease of coercivity with Pt thicknes while the energy barrier remains unaltered. These experiments can be explained by an induced magnetization within the Pt layer resulting in a kind of exchange coupled bilayer—in qualitative agreement with the exchange spring media described in this letter.

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