Multilayer Exchange Spring Media for Magnetic Recording

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Abstract:

The concept of exchange spring media is extended from two layers to $N$ layers. The coercive field of the multilayer structure decreases with $1/N$ while the energy barrier is only determined by the magnetic properties of the hardest layer. A 25 nm thick trilayer has a 7.5 times smaller coercive field (1.4T) as a single layer at the same thermal stability and for the same value of the magnetization. A continuous variation of the anisotropy in the recording media reduces the coercive field by a factor of 10 for a layer thickness of 25 nm.
High coercive materials such as FePt are suitable for high density recording. The high magnetocrystalline anisotropy permits small, thermally stable grains which in turn allow high recording densities. However, high coercive grains can not be written with conventional write heads\(^1\) even if the write field is applied at a large angle to the easy axis\(^2\), which reduces the switching field according to the Stoner-Wohlfarth theory. An increase of the spontaneous polarization reduces the write field but at the same time decreases the thermal stability because of larger demagnetizing fields \(^3\). In modern perpendicular media the loss of thermal stability owing to the demagnetizing field is partly compensated by intergrain exchange interaction that stabilizes neighboring grains. This stabilizing effect vanishes for too large demagnetizing fields (produced by large values of the spontaneous polarization \(J_s\)) where the grains rotate towards the in plane direction.

Recently, composite media and exchange spring media were introduced theoretically \(^4,5\) and experimentally by Wang et al.\(^6\) to reduce the write field requirements. In exchange spring media a magnetically hard layer and a magnetically softer layer are strongly exchange coupled. The coercive field of the hard magnetic layer is reduced by the exchange field of the neighboring soft magnetic layer. The magnetization reversal under the action of an external field of an exchange spring bilayer occurs in a two step process.

In a first step a nucleation in the soft layer is formed. In the limit that the soft layer is strongly exchange coupled to the hard layer and provided that the thickness of the soft layer \(t_s\) is larger than the domain wall width of the hard layer the nucleation field in the soft layer can be given as

\[
H_n = 2K_{\text{soft}}/J_s + 2A\pi r^2/(4t_s^2J_s),
\]

where \(K_{\text{soft}}\), \(J_s\) and \(A\) is the anisotropy, the spontaneous polarization and the exchange constant in the soft layer, respectively \(^7,8\). The last term accounts for the
exchange field from the hard layer that stabilizes the soft layer.

In a second step the formed nucleation propagates to the soft/hard interface where it becomes pinned. The bilayer completely reverses when the external field is large enough to overcome the pinning field $H_p$. Therefore, the switching field (coercive field) of the whole structure is given by, $H_c = \max (H_n, H_p)$. For the limit of an infinite thick soft layer coupled to an infinite thick hard layer analytical formulas for the pinning field $H_p$ at the interface were derived previously, without any focus on magnetic recording. Whereas Hagendorn\textsuperscript{9} took into account the difference in the anisotropy only, Kronmüller and Goll\textsuperscript{10} derived a more general formula which also includes a possible difference in the other intrinsic magnetic properties between the two layers.

Under the assumptions that the soft layer and the hard layer are not infinite but thick enough that a full domain wall fits inside each layer the analytical formula of Ref\textsuperscript{10} is still a very good approximation for $H_p$\textsuperscript{11}. The required soft layer thickness to form a full domain wall is given by $t = \pi \sqrt{A/K_{\text{soft}} + 2A/K_{\text{hard}}}$, which interestingly depends on the hard layer anisotropy $K_{\text{hard}}$\textsuperscript{11}. If not stated explicitly, in all following analytical estimations it is assumed that the soft layer is thick enough so that the second term in the nucleation field (exchange field) can be neglected. For the special case that the magnetization and the exchange constants are the same in both layers the pinning field can be written as,

$$H_p = \frac{1}{4} \times \frac{2(K_{\text{hard}} - K_{\text{soft}})}{J_s}$$

For zero anisotropy in the soft layer, the coercive field is reduced by a factor of 4 compared to
the coercive field of the hard layer alone. For higher values of the anisotropy in the softer layer the pinning field can even decreased further. The optimal value (obtaining the lowest coercive field) of the anisotropy in the soft layer is obtained if the nucleation field equals the pinning field. This is the case for $K_{\text{soft}} = 1/5K_{\text{hard}}^9$. The influence of $K_{\text{soft}}$ on the coercive field for exchange spring media with finite thickness was investigated by Dobin and Richter in detail $^{12}$.

The results of Ref $^{10}$ in the general form show that an additional reduction of the pinning field is possible by increasing either the magnetization or the exchange constant in the soft magnetic layer. However, a large magnetization in the soft layer also leads to a large demagnetizing field in the soft layer which in turn lowers the thermal stability. Micromagnetic simulation that take into account both coercivity and thermal stability have shown that the magnetization in the softer layer should be similar to the magnetization in the hard layer in order to maximize thermal stability for a given coercivity (or write field) $^{11}$. A good choice of the magnetic polarization, $J_s$, was found to be about 0.5 T. If experimentally the ratio of the exchange in the softer layer to the exchange in the harder layer can be increased the performance of exchange spring media can be improved. However, care has to be taken that larger values of the exchange constant in the soft magnetic layer require larger layer thicknesses because a significant reduction of the coercive field will only be possible if a full domain wall can be formed within the soft magnetic layer. According to Ref $^{10}$, a reduction of the exchange constant in the hard magnetic layer leads to a further reduction of the coercive field. Again, this accompanied by a decrease in thermal stability, since the maximum possible energy barrier is given by the domain wall energy.

A very interesting effect can be observed if the number of layers in exchange spring media is increased from two layer to $N$ - layers. First let us assume the case where the softest layer has
zero anisotropy. The anisotropy of the $m$-th layer is assigned according to \( K^n = (m-1)K_{\text{hard}} / (N-1) \). \( K_{\text{hard}} \) is the anisotropy of the hardest layer. With increasing number of layers the pinning field at an interface becomes smaller since the difference of the anisotropy of adjacent layers is decreased. The pinning fields at all interfaces are the same, given by

\[
H_{\text{pinning}} = \frac{1}{4} \times \frac{2(K^{n+1} - K^{n+1})}{J_s} = \frac{1}{4(N-1)} \times \frac{2K_{\text{hard}}}{J_s}
\]  

(2)

For a sufficient thick soft layer the pinning field determines the coercive field. For a finite value of the anisotropy in the softest layer the coercive field can be decreased even further. In this case \( H_c = 1/(4(N-1)+1) \times 2K_{\text{hard}} / J_s \). Therefore the coercive field of a trilayer and four layer structure can be reduced to 1/9 and 1/13 of the coercive field of the hardest layer, respectively. In principle every arbitrary hard magnetic grain can be switched at infinite small fields if the number of layers goes to infinity. This argument was discussed by Hagedorn as a possibility to resolve Brown’s paradoxon.

In order to test the concept of exchange spring multilayer for magnetic recording micromagnetic simulations are performed. In the micromagnetic simulation the value of the anisotropy constants of the layers are optimized to obtain the smallest coercive fields. However, to keep the thermal stability high the thickness of the hardest magnetic layer was constrained to be at least larger than the domain wall width in the hard layer that is about 7 nm. For all simulations the anisotropy of the hardest layer is \( K_{\text{hard}} = 2 \text{ MJ/m}^3 \). Although the investigated grain (diameter 5 nm, length 25 nm) reverses via nucleation the influence of the stray field can be very well described with an additional uniaxial anisotropy of the strength \( K_1 = 37 \text{ kJ/m}^3 \). The coercive field
of a trilayer structure (for the other parameters see FIG. 1) is compared with the coercive field of a single layer. The material parameters of the single layer are the same as in the hardest layer of the trilayer and bilayer. The external field is applied at an angle of 0.5 degree. FIG. 1 shows that the coercive field of the trilayer is reduced by a factor of 7.5 compared to the coercive field of the single layer alone. The discrepancy to the theoretical limit of 9 can be attributed to the finite layer thickness. For comparison also the hysteresis loops of bilayer structures with zero and non zero anisotropies in the softest layer are shown. For the bilayer with an anisotropy in the softer layer that is 16% of the anisotropy of the hard layer the smallest coercive field and perfectly rectangular hysteresis loops are obtained.

The concept of exchange spring media with varying anisotropies in each layer can be further extended by changing the anisotropy gradually. The pinning field of a domain wall in an inhomogeneous material is given by

$$H_{\text{pinning}} = \frac{1}{2} \frac{\partial E(x)}{\partial x} = \frac{1}{2} J_s \frac{\partial}{\partial x} \sqrt{AK(x)} / \partial x. \quad E(x) \text{ is the energy if the centre of the domain wall is located at the position } x. \text{ In the following } x \text{ is defined to be zero at the bottom of the grain and it is equal to the film thickness } t_G \text{ at the top of the grain.}$$

The domain wall energy density can be approximated by

$$E(x) = 4 \sqrt{AK(x)}.$$

The structure has the smallest coercive field if the strength of the pinning field is the same for each position of the domain wall. Therefore the pinning field must not depend on x. This can be realized if the anisotropy constant depends quadratically on x,

$$K(x) = \alpha x^2 = x^2 \frac{K_{\text{hard}}}{t_G^2}.$$

The grain has the maximum anisotropy ($K_{\text{hard}}$) at the top of the grain. For the pinning field follows,

$$H_{\text{pinning}} = \frac{1}{2} \frac{J_s}{J_s} \times \frac{\sqrt{AK_{\text{hard}}}}{t_G} / t_G. \quad (3)$$

The formula above is only valid if the value of the anisotropy does not change significantly at
typical distance of the domain wall width. This condition is not strictly fulfilled and therefore the quadratic dependence of $K_1$ is only an approximation. Detailed analysis applying a global optimization routine to find the optimal function $K_1(x)$ will presented elsewhere. For sufficient thick layers the coercive field equals the pinning field. The dependence of $K(x) = \alpha x^2$ leads to much smaller coercive fields than a trilayer structure for the same film thickness. This is in qualitative agreement with experiments on exchange spring media where the coercive field decreases if the ideal interface between the hard and soft layer is broadened due to annealing. A layer with this gradual change of anisotropy is called in the following G-layer. FIG. 1 shows that the coercive field is just 1/10 of the coercive field of the single layer structure (1.0 T). It is also interesting to note that the hysteresis loop is almost perfectly rectangular, which is indicated that the pinning field does not increase as a function of $x$. If the strayfield is taken into account the coercive field increases by about 3% which can be attributed to the additional uniaxial anisotropy caused by the shape anisotropy. In the region where the assumption of the analytically calculated pinning field is fulfilled (large $t_G$) Eq. (3) excellently agrees with the numerical calculation. If instead of a quadratic change of the anisotropy, $K_1$ is increased linearly as a function of $x$ the coercive field drastically increases to 2.0 T. FIG. 2 shows the reduction of the coercive field of a hard magnetic layer with a thickness of 20 nm and an anisotropy constant $K_{\text{hard}}$ that is coupled to a G-layer with thickness $t_G$ and a maximum anisotropy of $K_{\text{hard}}$. The coercivity reduction is calculated for different structures with different $K_{\text{hard}}$ values. The coercivity reduction $r = H_{\text{pinning}}/H_{c,\text{hard}}$ can also be calculated analytically using Eq. (3). For the reduction follows, 

$$r = (1/t_G)\sqrt{A/K_{\text{hard}}}.$$

Finally, it will be shown that the introduction of soft layers in principle do not influence the thermal stability at zero external field. The energy barrier of a single phase media (material
parameters are given in FIG. 1) is compared with the energy barrier of the trilayer of FIG. 3. The energy barrier is calculated using the nudged elastic band method\textsuperscript{14}. FIG. 3 shows that thermal fluctuations may form a nucleation at the end of the particle. This nucleation propagates through the particle. For the single phase media the formed domain wall has largest energy when it is located exactly in the centre of the grain. The energy barrier is equal to the domain wall energy in the hard region (for a cylindrical grain with diameter of 5 nm $\Delta E = 84 \ k_B T_{300}$).

Interestingly the situation is very similar for the trilayer structure. Again a domain wall is formed at the bottom of the grain. The energy of the domain wall successively increases as it is driven by thermal fluctuations in the harder layers. The domain wall has largest energy, when it is located in the hardest layer. Since the hardest layer has the same material properties as the single grain the domain wall energies are the same. Due to the finite layer thickness of 7nm of the hardest layer in the trilayer, not a full domain wall is formed, leading to a reduction of the energy barrier of about 7%. The energy barrier of G-layer with thickness of 25 nm is about 30% smaller than that of the single layer. However, the energy barrier can be increased by coupling the G-layer to a hard magnetic layer with constant anisotropy and matching the values of the anisotropies at the interface. The thermal stability is only determined by the magnetic properties in the hardest magnetic layer.

In conclusion it was shown that an optimal design of a magnetic bilayer structure for recording media requires a hard magnetic layer with properties similar to state of the art perpendicular recording media. This hard layer is coupled to a second layer that has in the optimal case an anisotropy that is about five times larger. Most important it was demonstrated that the energy barrier in multilayer exchange spring media is not proportional to the coercive field. The coercive field is proportional to one over the number of layers while the energy barrier is
constant.

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References:


FIG. 1. Hysteresis for different magnetic grains of a recording media. Total grain thickness 25 nm for all structures. Grain diameter is 5 nm. (single phase) The whole grain is of a magnetic hard material $K_1 = 2 \text{ MJ/m}^3$. (bilayer $K_{\text{soft}} = 0$) 12.6 nm of the grain are magnetically very hard with $K_{\text{hard}} = 2 \text{ MJ/m}^3$ the other 12.4 nm are perfectly soft $K_{\text{soft}} = 0$. (bilayer $K_{\text{soft}} = 0.32 \text{ MJ/m}^3$) 12.6 nm are again extremely hard $K_{\text{hard}} = 2 \text{ MJ/m}^3$. The 12.4 nm thick softer region has still a relative high anisotropy of $K_{\text{soft}} = 0.32 \text{ MJ/m}^3$. (trilayer) 7 nm with $K^3 = K_{\text{hard}} = 2 \text{ MJ/m}^3$, 7 nm with $K^2 = 1.0 \text{ MJ/m}^3$ and 11 nm with $K^1 = 0.125 \text{ MJ/m}^3$. (continuous strayfield) The anisotropy increases quadratically as a function of the distance from the bottom of the grain. The demagnetizing field of the grain is taken into account. (continuous) The demagnetizing field is omitted.

FIG. 2. Reduction of the coercive field if a layer with gradually increasing anisotropy of thickness $t_g$ and a maximum anisotropy of $K_{\text{hard}}$ is fully exchange coupled to a hard magnetic layer. The value of the anisotropy constant $K_{\text{hard}}$ of the hard layer is changed from 1 MJ/m$^3$ to 4 MJ/m$^3$.

FIG. 3. Energy barrier and thermally activated switching process for a single phase media and the trilayer of Fig. 1. The hardest layer of the trilayer is 7 nm. The grain diameter is 5 nm. The $z$-component of the magnetization during thermally activated switching is color coded.
Fig. 1.
Fig. 3.