MICROMAGNETICS OF EXCHANGE SPRING MEDIA:
OPTIMIZATION AND LIMITS

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Abstract: The magnetic properties of exchange spring media are compared with perpendicular recording media using simple analytical estimates and using micromagnetic simulations. For a hard layer exchange coupled to a perfectly soft layer the theory predicts a coercive field of the entire system of 1/4 of the anisotropy field of the hard layer in the limit of infinite layer thicknesses. A value of the coercive field close to the maximum reduction can be achieved for soft layers that are thicker than \( l_h \) where \( l_h^2 = \frac{2\pi^2 A_s}{K_h} \). \( A_s \) is the exchange constant in the soft layer and \( K_h \) the anisotropy constant of the hard layer. For multilayer structures with gradually decreasing anisotropy in each layer the coercive field can be decreased even further. A genetic optimization algorithm is used to design a bilayer structure as close as possible to the theoretical limit. The optimization shows that a gain in energy barrier of about 70\% can be expected practically in exchange spring media with two layers and zero anisotropy in the soft layer. The switching time of exchange spring media for external fields applied 10° off the easy axis is about 0.4 ns which is comparable to single phase media.
1. Introduction

Hard disk drives for ultra high storage densities require small grain sizes to fulfill the requirements for high signal to noise ratios. However as the grains become too small the bits are no longer stable. This effect is known as superparamagnetic limit. It has its origin in thermal fluctuations which lead to spontaneous switching of the magnetization. In small magnetic particles the energy barrier for thermally activated switching is given by the product $K \times V$, where $K$ is the magnetocrystalline anisotropy constant and $V$ is the grain volume. Thus the reduction of grain size can be balanced by a large anisotropy. Charap et al. [2] determined an upper bound for the areal density of 40 GBits/in². However, new methods have been developed that allow to overcome this limit such as perpendicular recording and antiferromagnetically-coupled (AFC) media (Fullerton et al. [7] and Abarra et al. [1]).

Most new concepts for ultra high density recording are based on high coercive materials such as FePt, CoPd and CoPt. Chemically ordered FePt alloys have a magnetocrystalline anisotropy constant in the order of $7 \times 10^6$ J/m³ which is more than ten times larger than that of currently used Co based alloys. Such a high anisotropy will ensure thermal stability at small grain sizes leading to an areal density in the Tbit/in² regime [35]. However, conventional recording systems based on highly coercive grains require a write field that is higher than write field provided conventional single pole heads. The write field of is limited by the magnetic moment of the pole tip material [13]. The maximum write field achievable with standard head design is about 1.8 T [18].

Thermally assisted recording is possibility to overcome the writing problem [23]. Thiele et al. combined the idea of thermally assisted recording with a media composition consisting of a FePt/FeRh bilayer system [36]. Their idea is based on a hard layer which is exchange coupled to an antiferromagnetic layer. After heating the antiferromagnetic layer upon a transition temperature it becomes ferromagnetic with a large magnetic moment and low magnetocrystalline anisotropy. Thus upon the transition temperature the antiferromagnetic layer acts as a magnetic soft layer, which helps to reverse the hard layer.

Victora and Shen proposed magnetic multilayer structures being composed of magnetically hard and magnetically soft layers [33]. In the model of Victor and Shen, 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 significantly. This is different to other work where the inhomogeneous states, which are formed in the soft layer and in the hard layer during reversal are sufficient to decrease the coercive field [30]. A reduction of the exchange coupling between the hard and the soft layer by a coupling layer is not required, in order to decrease the coercive field.

Section 2 to section 4 deal with single phase perpendicular recording media. In section 2 the basic principles and the limits concerning thermal stability are reviewed. A more detailed analysis of the thermal stability is given in section 3. In particular the influence of the layer thickness on the thermal stability is calculated numerically. The switching time in perpendicular recording is investigated in section 4. The following sections mainly deal with exchange spring media. The basic idea of exchange spring media is shortly described in section 5. Section 6 and section 7 address the problem if the interaction fields between grains in exchange spring media and perpendicular recording media can be treated in a mean field approach. In the following chapters this mean field approach is used to reduce the computational time to determine the saturation field of the recording media and to calculated the energy barrier of the most unstable grain in a bit. The coercive field of a bilayer structure for different soft layer thicknesses is calculated in section 8. The influence of different hard layer thicknesses of a bilayer structure on the thermal stability is treated in section 9. In exchange spring media materials with different values of the spontaneous polarization can be used for the hard layer and the soft layer. The influence of different $J_s$ values in both layers on the energy barrier and saturation field is investigated in section 11. The switching times of exchange spring media are calculated in section 12. Finally, a global optimization algorithm is applied to calculate the optimal bilayer structure for a given total layer thickness and a given saturation field.

2. Perpendicular recording media

Perpendicular recording is believed to be the future technology after longitudinal recording. Recently, the first hard disks based on perpendicular recording were shipped [16,17]. In perpendicular recording the magnetization is oriented vertically to the film plane. One of the main advantages of perpendicular recording is that the different head design which includes a soft underlayer allows larger head fields compared to longitudinal recording. A
major difference to longitudinal recording is that in perpendicular recording demagnetization fields lead to an enhanced decay rate of the signal at low linear densities, in particular if the media magnetization, $M_s$, is close to $H_c$, the coercive field of the media. In longitudinal recording, head to head domain walls at high data densities are the limiting factor of the areal densities. Concerning thermal stability the worst case in perpendicular recording is a uniformly magnetized disk. This is usually avoided by channel encoding [34], which avoids long segments of uniformly magnetized tracks. Beside the stability problem the readback signal of a uniformly magnetized medium is zero, which leads to problems in the reading process and in the channel synchronization. Nevertheless, it has to be taken into account that ten or more neighboring bits have a magnetization that points in the same direction in one track. For a flux density of about 1300 kfcI this would relate to a distance of about 200 nm. For a layer thickness of about 20 nm the uniformly magnetized region can be regarded in a good approximation as an infinite extended film that has a demagnetizing field of

$$\mu_0 H_d = -\mu_0 N M_s,$$

with a demagnetizing factor $N$ equal to 1.

In perpendicular recording the grain that is exposed to the largest demagnetizing field is usually the grain in the center of a bit. Therefore that bit is the most unstable one. The demagnetizing field can be taken into account with a mean field that adds to the external field. The demagnetizing field is partially compensated by the exchange field between neighboring grains in the media. However, the strength of the intergrain exchange is limited by the signal to noise ratio. As the exchange between grains becomes too large the transition between neighboring bits is not located solely in the grain boundary but a domain wall between the bits is formed. As a consequence the transition jitter increases leading to a reduction of the signal to noise ratio. Therefore moderate values of the exchange field of about 5% of the anisotropy field are proposed by Gao et al. [8]. In practice it seems very probably that for perpendicular recording media with areal densities of about 500 Gbit/inch² much larger values of the intergrain exchange are used to achieve the required thermal stability. A simple analytic estimate for the optimal material parameters and for the limits of the thermal stability for perpendicular recording can be found in ref
[30]. The analytical estimate is based on a mean field approach. It assumes that the effective field that acts on the grain in the centre of a bit can be written as,

$$\mu_n H = -\mu_n NM_z + B_{ex},$$

where $N$ is the demagnetizing factor. In the following $N$ is assumed to be one. The mean field exchange field acting on the center grain, produced by all neighbors, is given by $B_{ex}$. A realistic assumption for the demagnetizing field is about -0.5 T and a mean field exchange field of 0.2 T. These two fields lead to an effective mean field at remanence of about -0.3 T.

3. Energy barrier and thermal stability of single phase perpendicular media

The energy barrier of a single domain particle can be written as,

$$\Delta E = KV\left(1 - \frac{H}{H_c(\theta)}\right)^n,$$

where $H_c(\theta)$ is the Stoner–Wohlfarth switching field at an angle $\theta$ to the anisotropy axis [37]. The exponent $n$ is 2 for the special case that the external field $H$ is applied parallel to the easy axis. If the angle $\theta = 15.9^\circ$ the exponent $n$ is very close to 3/2 [11]. The value $n$ decreases with decreasing field below 15.9° and increases with increasing field above 15.9°. For an angle $\theta = 1^\circ$ the exponent changes from 1.62 to 1.85 as the field changes from $H_c$ to zero.

If the reversal mode is triggered by nucleation the exponent can be approximated by 3/2 [6]. As suggested by Eq. (3) the thermal stability can be enhanced as the film thickness (the volume depends linearly on the film thickness) is increased. However, as the film thickness becomes to large the energy barrier can not be increased any further. This can be understood by a simple analytical estimate. In the following, $F$ denotes the area of the basal plane of one grain. The energy required to form a domain wall is $E_{wall} = 4F\sqrt{AK_1}$, while the energy required to rotate the particle coherently is $E_{rot} = K_1 V$. Now, if the particle length is increased, only $V$ increases while $F$ remains constant. Thus, there will be a
critical length where $E_{\text{wall}} < E_{\text{ref}}$ and the nucleation and expansion of a domain wall becomes energetically favorable. For an exchange constant of $A = 10 \text{ pJ/m}$ and an anisotropy of $K = 300 \text{ kJ/m}^3$ the critical length becomes $l_{\text{crit}} = \sqrt[4]{\frac{A}{4K_1}} = 4\delta_B = 23 \text{ nm}$. $\delta_B$ denotes the Bloch parameter of the particle.

For a detailed analysis of the energy barrier as a function of the film thickness the energy barriers between the state with magnetization up (initial state) and the state with magnetization down (final state) are calculated for various film thicknesses using the nudged elastic band method [4]. The column length is varied from 10 nm to 70 nm. Fig. 1 shows the maximum exchange energy and the effective volume for the thermal reversal of an elongated particle as a function of the column length. The maximum exchange energy that occurs during reversal is a measure for the homogeneity of the magnetization. If the maximum exchange energy remains zero the particle reverses by uniform rotation. The calculated energy barrier can be expressed as $\Delta E = K_1 V_{\text{eff}}$, where $V_{\text{eff}}$ is effective volume of the particle. The diameter is 13 nm. Above a size of 20 nm the reversal mode becomes inhomogeneous. Below 20 nm the maximum exchange energy is almost zero. Here, the particle reverses by coherent rotation which is in very good agreement with the simple analytical estimate. Above 40 nm the particle is large enough to form a full domain wall. A further increase of the length does not change the maximum exchange energy any more. Once the wall is formed it only moves through the particle. The same is true for the energy barrier, here expressed as an effective switching volume. Above 40 nm the effective volume $V_{\text{eff}}$ saturates. Therefore a further increase of the column length of the grains does not increase the thermal stability in single phase perpendicular recording material.

4. Switching times of single phase perpendicular media

Besides the areal density another important problem in magnetic recording is the data rate. As the data rate approaches the GHz regime the switching time comes in the order of the precessional frequency. A profound knowledge of the switching process is a prerequisite for further optimization. Mallinson [21] analytically derived the switching time as a function of the field strength for fields parallel to the anisotropy direction. He and Doyle [12] solved the Landau-Lifshitz equation numerically, in order to investigate switching with very short field pulses. They found that if the rise time of the field pulse is less than a few
nanoseconds and the Gilbert damping constant $\alpha \ll 1$, switching can occur well below the Stoner-Wohlfarth limit.

In the following we will discuss the switching time for small magnetic particles. The Landau-Lifshitz Gilbert equation was solved numerically for a single magnetic moment using a backward differentiation method. Here we use the previous results (shown in Fig. 1) that small particles reverse uniformly. The shape anisotropy which is neglected may be added with an additional anisotropy term. The angle between the external field and the easy axis is changed from $1^\circ$ to $10^\circ$ and $45^\circ$. The field rise time $t_r$ is varied from 0.001 ns to 1 ns. Within this time the external field is increased linearly from zero to its maximum value. The material parameter of the investigated grain are $J_s = 0.5$ T, $A = 10^{-11}$ J/m, $K_1 = 3 \times 10^5$ J/m³ which leads to an anisotropy field of $\mu_0 H_a = 1.5$ T. The damping constant is $\alpha = 0.02$. To calculate the switching time we look at the time evolution of the z-component of the magnetization. The critical point when the z-component of the magnetization crosses zero the last time defines the switching time $t_s$. This guarantees that all field pulses longer than $t_s$ will switch the particle. Consequently for field pulses longer than $t_s$ switching is not sensitive on the exact duration of the field pulse. The exact duration of the field pulse is one major concern in precessional switching [31].

Fig. 2 shows the switching time when the external field is applied at an angle of $1^\circ$. Depending on the rise time of the external field, different dependencies of the switching time as a function of the external field strength are obtained. For field rise times, $t_r$, larger than 0.1 ns one observes the expected decrease of the switching time with increasing field strength. Furthermore, the simulations show an almost linear relationship between the switching time and field rise time for $t_r > 0.1$ ns.

The situation completely changes when the field rise time becomes smaller than $t_r < 0.1$ ns. Then, precessional effects dominate the switching behavior. Three interesting effects can be observed:

- Switching well below the Stoner - Wohlfarth limit is possible [12]
- The switching time increases with shorter field rise times.
- The switching time does not decrease with increasing external field strength monotonically, but shows a maximum slightly above the Stoner Wohlfarth switching field [28, 9, 32].
As the external field is applied at an angle of $10^\circ$ the fastest switching time at low external field can be decreased by more than a factor of 4 as shown in Fig 3. Fast reversal modes do not longer occur for field rise times of 0.1 ns or larger. As expected the fastest switching occurs for an angle of $45^\circ$. The particle can be switched with field pulses shorter than 0.06 ns at fields of 0.6 T as shown in Fig. 4.

5. The concept of exchange spring media

In perpendicular recording each grain is composed of one magnetic phase. Every grain can be regarded as a single domain particle. Perpendicular recording media have the drawback that both the coercive field and the energy barrier depends linearly on the anisotropy constant. However, what is needed is a magnetic recording media that has a sufficient small coercive field so that it can be written with conventional recording heads but has a sufficient high thermal stability to support high recording densities. Any increase of the magnetization of the recording layer lowers the switching field according to

$$\mu_0 H_c = \frac{2K}{M_s}.$$ 

However, a high magnetization will increase the demagnetization field of the media which in turn decreases the thermal stability as discussed previously.

In the following the basic principle of the exchange spring media is explained. The basic idea is to combine a soft magnetic layer and a hard magnetic layer. The soft layer helps to reverse the grain. The purpose of the hard layer is to provide the thermal stability. Under the assumption that both layers remain completely homogeneous and both layers are perfectly exchange coupled the bilayer structure would not lead to any benefit compared to a single layer system. The bilayer system could be described with one average magnetization $M_{\text{eff}} = (M_{\text{hard}} \cdot l_{\text{hard}} + M_{\text{soft}} \cdot l_{\text{soft}})/(l_{\text{soft}} + l_{\text{hard}})$ and one average anisotropy constant $K_{\text{eff}} = (K_{\text{hard}} \cdot l_{\text{hard}} + K_{\text{soft}} \cdot l_{\text{soft}})/(l_{\text{soft}} + l_{\text{hard}})$ [27]. In a simple model the energy barrier can be estimated by

$$\Delta E = K_{\text{eff}} \cdot F \cdot (l_{\text{soft}} + l_{\text{hard}}),$$

where $F$ is the area of the basal plane of one grain of the media. The coercive field is $\mu_0 H_c = 2K_{\text{eff}} / M_{\text{eff}}$. The ratio energy barrier to coercive field $\Delta E / H_c$ only depends on the value of the average magnetization and the grain volume. Therefore the bilayer structure with $M_{\text{eff}}$ and $K_{\text{eff}}$ has the same energy barrier and the same coercive field as the corresponding single layer structure ($M_{\text{single}}=M_{\text{eff}}$ and $K_{\text{single}}=K_{\text{eff}}$). However, detailed micromagnetic simulations show that the assumption of homogeneous reversal of the hard layer and the soft layer is not valid for most compos-
ite structures consisting of exchange coupled soft and hard layers [30]. During field induced reversal the soft layer acts as a magnetic spring that initiates the reversal of the hard layer similar to what is observed in composite permanent magnets [26]. A magnetic domain wall is created next to the hard/soft interface. The coercive field of a bilayer structure can be reduced to one quarter of the anisotropy field if the anisotropy in the soft layer is zero [19,20]. 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 activation may lead to switching of the particle. The reversal process which is induced by thermal activation is more homogeneous than the reversal mode by applying of the switching field [30]. No domain wall is formed in the soft phase. For an optimum hard layer thickness the energy barrier of the homogeneous reversal mode is about the same as the domain wall energy in the hard layer. For slightly smaller hard layer thicknesses the reversal mode is homogenous rotation. Hence, in the highest energy state between the initial state and the reversed state (saddle point) the magnetization of the hard layer points in the hard axis direction. In order to minimize the total energy the soft layer magnetization is homogenous pointing parallel to the hard layer. Due to the different reversal modes of the field induced switching process and the temperature induced switching process the ratio of the energy barrier over the coercive field is not constant. It can be optimized by the magnetic properties of the bilayer structure.

6. Mean field approach

For sufficient small intergranular exchange between grains the magnetization in every grain remains homogeneous. The influence of neighboring grains can approximately be taken into account in a mean field approach.

6.1. Exchange field

Let us calculate the switching field of grain \( j \) exchange coupled to a grain \( i \) as shown in Fig. 5. The exchange coupling strength between surface spins of each grain is given by the exchange integral \( J \). The spin operators are approximated as classical vectors, \( \mathbf{S}_i \) and \( \mathbf{S}_j \). \( \mathbf{M} \) is the magnetization vector of grain \( j \), \( \mathbf{H} \) is the external field. The magnetization of grain \( i \)
is fixed in the up direction. In order to derive the exchange field on grain $j$ the total energy of grain $j$ is calculated,

$$E_j = -\int \mu_0 \mathbf{M} \cdot \mathbf{H} dV - J \sum_i S_i S_j$$  \hspace{1cm} (4)

The sum runs over all atoms at the interface between the grain $i$ and grain $j$. Replacing the sum in Eq. (4) by an integral over the surface yields for a cubic lattice,

$$E_j = -\int \mu_0 \mathbf{M} \cdot \mathbf{H} dV - \frac{JS^2}{a^2} \int_{S_j} \mathbf{u}_i \cdot \mathbf{u}_j dF$$  \hspace{1cm} (5)

where $a$ denotes the lattice constant, $S$ is the total spin quantum number of an atom, and $\mathbf{u}_i$, $\mathbf{u}_j$ denote the spin directions. Using the definition $A^{\text{int}} = \frac{JS^2}{a}$ which gives the intergrain exchange constant, and replacing the surface integral with a volume integral over grain $j$ gives,

$$E_j = -\int \mu_0 \mathbf{M} \cdot \mathbf{H} dV - \frac{A^{\text{int}} S}{\mu_0 M_s} \cdot \mu_0 M dV$$  \hspace{1cm} (6)

where $t$ is the width of grain $j$ and $M_s$ is the magnetization of grain $j$. The exchange field is given by the field when both energy terms in the equation above are equal. The magnitude of this field can be given by,

$$H_{\text{ex}} = \frac{A^{\text{int}}}{\mu_0 M_s t}$$  \hspace{1cm} (7)

which is called exchange field in the following. To calculate the exchange field for a grain with a circular basal plane with a diameter $d$ (which is completely surrounded by neighboring grains) we first rewrite Eq. (5) to get

$$E_j = -\mu_0 \mathbf{M} \cdot \mathbf{H} V - \mu_0 \mathbf{M} \frac{A^{\text{int}} \mathbf{u}_i}{\mu_0 M_s} \cdot \frac{F}{V} \hspace{1cm} (8)$$
where $F$ is the grain boundary area and $V$ is the volume of the grain. It is assumed that the magnetization is homogeneous within the grain. $u_i$ denotes the average magnetization of the neighboring grains. For $F = d \pi h$ and $V = d^2/4 \pi h$ one gets,

$$\begin{align*}
H_{ex} &= \frac{A^{\text{int}} F}{a \mu_0 M_s^3 V} = \frac{4 A^{\text{int}}}{a \mu_0 M_s^3 d}.
\end{align*}$$

(9)

It is interesting to note that Eq. (9) is also valid for a grain with a square basal plane with edge length $d$ which is completely surrounded by neighboring grains.

### 6.2. Demagnetizing field

The demagnetizing field significantly influences the magnetic properties in perpendicular recording. Firstly, the elongated shape of every grain leads to a shape anisotropy caused by the demagnetizing field. The shape anisotropy can be described with an uniaxial anisotropy with an anisotropy constant

$$K_{\text{shape}} = \frac{1}{2} \mu_0 M_s^2 (n_x - n_z) .$$

(10)

The demagnetizing factors are positive values and usually obey $n_x + n_y + n_z = 1$. The constraint that the sum of all demagnetizing factors is one will be modified if a soft magnetic underlayer is taken into account [22]. The demagnetizing factors of cylindrical grains are compiled for different ratios of the diameter over particle height by Chen et al. [3]. For example for a particle with a diameter of 4.4 nm, a particle high of 14 nm and a polarization of 0.5 T the shape anisotropy is $K_{\text{shape}} = 3.5 \times 10^4$ J/m$^3$.

The second effect caused by the demagnetizing field is that the magnetization of a fully saturated recording media favours the reversal of individual grains, at least as long as the exchange field is smaller than the demagnetizing field. Care has to be taken when considering demagnetizing field of a bilayer with different values of the spontaneous polarizations in both layers. The simple assumption that an average demagnetizing field acts over one grain is wrong. Each layer has to be taken into account separately. For a finite area of uniform magnetization the demagnetization fields is calculated numerically. Fig. 6 shows the demagnetizing field of a bilayer (with an extension of 80 nm x 80 nm) with different
values of the spontaneous magnetic polarization, $J_s$, in the two layers. In the bottom layer, where the polarization is zero, a very small stabilizing field of about 0.2 T acts on the magnetization. In the top layer with a spontaneous polarization of 2 T the $z$-component of the demagnetizing field is about 1.8 T in the center. An average spontaneous polarization $J_{s,\text{average}}$ would predict a demagnetizing field $\mu_0 H_d = -N_z J_{s,\text{average}}$ of 1 T. A reasonable approximation of the numerical result above assumes an infinitely extended area with the magnetization pointing in the same direction which will give a demagnetizing field in the soft layer $\mu_0 H_{d,\text{soft}} = -N_z J_{s,\text{soft}}$ and a demagnetizing field in the hard layer of $\mu_0 H_{d,\text{hard}} = -N_z J_{s,\text{hard}}$. This approximation slightly overestimates the demagnetizing effects and thus will give a lower bound for the energy barrier. The influence of different spontaneous polarization on the energy barrier and the coercive field in a bilayer structures is investigated in detail in section 11.

7. Comparison of the mean field approach with FE simulation

To validate the mean field approach, it is compared with a more realistic model. A finite element model of a media with 15 x 14 grain was used to calculate the switching field and the energy barrier of the center grain. In the finite element model every grain is discretize which allows to resolve possible magnetization inhomogeneities within a grain. All 15 x 14 grains are simulated simultaneously. Thus the exchange field and the magnetostatic field are rigorously evaluated using the finite element method [29]. For the calculation of the energy barrier initially all grains point up and the energy barrier that is required to reverse the centre grain is calculated using the nudged elastic band method [4]. For the calculation of the saturation field the magnetization of all grains point down except the centre grain that still points up. The external field points down with a very small angle between the $z$-axis in order to break the symmetry. For the single phase media the following parameters were used: Intergrain exchange $A^{\text{int}} = 1 \times 10^{-14}$ J/m, spontaneous magnetic polarization $J_s = 0.5$ T, intragrain exchange $A = 10^{-11}$ J/m, magneto-crystalline anisotropy $K_1 = 3.0 \times 10^5$ J/m$^3$. The film thickness is 14 nm. Under the assumption that the basal plane of the center grain can be approximated by a circle, the effective grain diameter is 4.4 nm. For the exchange spring media the parameters are $A^{\text{int}} = 1 \times 10^{-14}$ J/m, $J_{s,\text{hard}} = J_{s,\text{soft}} = 0.5$ T, $A = 10^{-11}$ J/m, $K_{1,\text{hard}} = 1.0 \times 10^6$ J/m$^3$, and $K_{1,\text{soft}} = 0$. The hard layer
thickness is 7 nm and the soft layer thickness is 7 nm. The average grain diameter is 4.4 nm. For both systems the volume of the center grain is 215 nm$^3$.

Table 1: Energy barrier ($k_B T_{300}$) and saturation field (T) of the single phase media and an exchange spring media. The single layer values can be compared with a mean field approach. Calculations taking into account the stray field (with $B_d$) and taking into account the exchange field between grains (with $B_{ex}$) are compared with simulations neglecting interactions (no $B_{ex}$, no $B_d$). The mean field exchange field is 0.23 T, and the mean field demagnetizing field is 0.3 T.

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First the switching field of the center grain was calculated numerically by solving the Landau-Lifshitz equation for all 15 x 14 grains. The calculated switching fields are $\mu_0 H_c = 1.66$ T for the single phase medium and $\mu_0 H_c = 1.47$ T for the exchange spring medium. The simulations were repeated assuming zero intergrain exchange interaction. For the single phase media the difference in switching fields calculated with and without intergrain interaction was 0.26 T. This value should be equal to the intergrain exchange field. The mean field exchange field is 0.22 T according to Eq. (7). These results show that the mean-field value and the micromagnetically calculated value for the exchange field are in good agreement. The small deviations may result from the assumption that the grain of the FE simulation has a circular basal plane. Furthermore the spins of the neighboring grains do not point exactly parallel to the z-axis. An easy axis distribution with a standard deviation of 2° is assumed.

The calculation of the exchange field was repeated for the exchange spring media. Although during reversal in exchange spring media inhomogeneous states are formed the
mean field exchange field very well describes the intergrain interaction. The difference between the switching field with and without exchange interaction is 0.24 T.

Secondly the energy barriers were calculated micromagnetically for the entire system. For the single phase medium the numerical result can be compared directly with the analytically calculated value using a mean field approximation for the exchange field and for the demagnetization field. In both, the micromagnetic simulations and in the analytic calculations the interaction fields can be added systematically. In the following we show how the exchange field and the demagnetization field will change the energy barrier of the center grain.

The energy barrier of the center grain omitting the demagnetizing field of the film and neglecting the intergrain exchange between neighboring grains is given by $\Delta E = KV$. The values of the mean field approach for the single phase media perfectly agrees with that obtained from the finite element simulations as shown in Table 1. If we take into account the demagnetizing field in the finite element simulations two effects have to be considered. Firstly, the demagnetizing field within the grain is responsible for an energy term that can approximated by an uniaxial anisotropy. In the investigated sample the ratio diameter to particle height is 0.314, which leads to a shape anisotropy constant of $3.5 \times 10^4 \text{ J/m}^3$ [3].

Secondly, the thin film with perpendicular anisotropy produces a demagnetizing field. Due to the limited lateral dimension of the investigated sample the demagnetizing field of the film is about 0.3 T this is significantly smaller than the value of the demagnetizing field of an infinite extended film of 0.5 T. Using Eq. (3) the energy barrier under the influence of the demagnetizing field can be calculated. The demagnetizing field of the film is considered in the field $H$. Since the demagnetizing field does not act exactly perpendicular to the film normal the exponent $n$ in Eq. (3) is set to 3/2. The shape anisotropy is added to the anisotropy constant and hence modifies $K_1$ and $H_c$. For the single phase media the demagnetizing field reduces the energy barrier to 12.86 $k_B T_{300}$. This is in excellent agreement with the finite element simulations predicting an energy barrier of 12.8 $k_B T_{300}$. Additionally taking into account the exchange field, the total mean field acting on the center grain is reduced to 0.08 T. The energy barrier increases to 21.1 $k_B T_{300}$. 
The results from the numerical simulation are presented in Fig. 7. Fig. 7 shows the total energy along the minimum energy path calculated with the nudged elastic band method for switching the center grain of the single phase medium. In conclusion, Table 1 shows that although the demagnetizing field is larger than the exchange field the energy barrier increases if both the exchange field and the demagnetizing field are taken into account. The reason is that magnetostatic effects lead to shape anisotropy which increases the total anisotropy of the particle. It is also interesting to mention that only an exponent $n$ in Eq. (3) of $3/2$ leads to a good agreement between the analytical calculations and the finite element calculations.

The above results show that the mean field approach gives very good estimates for the interaction fields. Thus it is possible to consider only a single grain and take all interaction into account by means of equation Eq. (2), in order calculate the switching field and the energy barrier of perpendicular recording media. For composite media the magnetization will become non-uniform within a single grain. Therefore the calculation of the magnetic properties still requires the use of the finite element method: 3D micromagnetics is used to resolve the magnetization within a single grain, whereas the mean field method gives the interaction field acting on the grain like an external field. In the following this combination of finite element simulation and mean field method is used to calculate switching fields and energy barriers. An overestimation of demagnetizing effects using a demagnetization factor of $N_z = 1$ gives a lower bound for the energy barrier.

8. Coercive field of a bilayer structure

The Stoner Wohlfarth theory gives for the nucleation field of single domain particles

$$H_c = 2K_1/J_s \gamma(\theta),$$

(11)

where $\gamma(\theta)$ depends on the angle between the easy axis and the external field. For $\theta$ equal to zero the factor $\gamma$ is one. For a bilayer structure where a soft magnet is exchange coupled to a hard magnet an analytical solutions can be given in the limiting case of an infinite thick soft magnetic layer and an infinite thick hard magnetic layer. Kronmüller and Goll calculated the coercive field for different exchange constants ($A$), different magnetization ($J$) values and different anisotropy constants ($K$) values in the hard and soft layer [19]. It is
assumed that the uniaxial directions in the soft layer and the hard layer are parallel. Neglecting the demagnetizing field the coercive field can be given by

\[
H_c = \frac{2K_h}{J_h} \frac{1 - \varepsilon_K \varepsilon_A}{(1 + \sqrt{\varepsilon_J \varepsilon_A})^2},
\]

where

\[
\varepsilon_K = \frac{K_s}{K_H}, \quad \varepsilon_J = \frac{J_s}{J_H} \quad \text{and} \quad \varepsilon_A = \frac{A_s}{A_H}.
\]

The parameters with the index \(S\) and \(H\) denote the soft layer and the hard layer, respectively. Assuming that the magnetic polarization and the exchange constant is the same in both layers, the formula can be simplified to

\[
H_c = \frac{(2K_{1,\text{hard}} - 2K_{1,\text{soft}})}{4J_s}.
\]

From Eq. (14) follows that for zero anisotropy in the soft layer the coercive field of a hard layer is reduced by a factor of four. Using soft layers with higher values of the magnetic polarization or higher anistropy decreases the coercive field of the bilayer structure even further. For perpendicular recording, however, a bilayer structure with a very large value of \(J_s\) in the soft layer may be undesired because of large demagnetizing fields. This aspect is treated in detail in section 11. The anisotropy in the soft layer just has to be small enough to allow for a nucleation at small fields.

Eq. (14) is valid in the limit for an infinite thick hard and soft layer. Leineweiber and Kronmüller calculated the nucleation field of hard/soft/hard layers in the limit of strong interface coupling between the layers [14]. Guslienko et al. calculated the nucleation field in the limit of strongly and weakly exchange coupled hard soft layers as well as the switching field of hard/soft bilayers in the limit of weak interlayer exchange coupling [10]. In order to investigate the reduction of the coercive field of strongly exchange coupled bilayer structures, finite element micromagnetic simulations are performed. The model is explained in detail in Ref [29]. The exchange coupling between the hard and the soft layer is not reduced compared to its bulk value. Therefore, even during reversal the angle between neighboring spins across the interface is small. Hence, the spin angles can be rep-
resented with a continuous function of space which is the requirement of any micromagnetic simulation. For weak exchange coupling across the interface this requirement is no longer fulfilled. The function of the magnetization has to be split into two functions which are coupled across the interface. Garcia et al. coupled these functions via an atomistic model across the interface [24, 25].

Fig. 8 shows the demagnetization loop of a bilayer structure for different thicknesses of the soft layer. The anisotropy of the hard layer is $K_{\text{hard}} = 1 \times 10^6 \text{ J/m}^3$. The hard layer thickness is 20 nm. The anisotropy of the soft layer was assumed to be zero. The magnetic polarization is $J_{s,\text{hard}} = J_{s,\text{soft}} = 0.5 \text{ T}$. The intragrain exchange constant is $A = 1 \times 10^{-11} \text{ J/m}$. For all investigated soft layer thicknesses the external field nucleates a reversed domain in the soft layer. The domain wall becomes pinned at the hard/soft interface. When the external field exceeds the pinning field the reversed domain expands through the entire bilayer ending up in the reversed state. It is interesting to note that the $z$-component of the magnetization remains nearly constant until a critical field is reached. For external fields larger than this critical field the magnetization drastically drops. In the limit of thick soft layers this critical field agrees well with the nucleation fields given in Ref [10].

Fig. 9 to Fig. 11 show the coercive field of the bilayer structure for hard layers with different anisotropy constants. The coercive field is given as a function of the thickness of the soft magnetic layer. The anisotropy constant in the hard layer varies from $K_{\text{hard}} = 0.25 \times 10^6 \text{ J/m}^3$ to $K_{\text{hard}} = 4 \times 10^6 \text{ J/m}^3$. The angle between the easy axis and the external field is $0.5^\circ$. Fig. 9 to Fig. 11 show that soft layer thicknesses larger than 15 nm are sufficient to decrease the coercive field nearly by a factor of 4. The required thickness of the soft layer thickness to decrease the coercive field by almost a factor four can be estimated as follows. The coercive field can be decreased by one quarter if a whole domain wall is formed in the soft layer. However, the required soft layer thickness can not be approximated by the typical domain wall width in the soft layer which can be written as $l_s = \pi \sqrt{2\mu_0 A/J_{s}^2}$. The domain wall width in the soft layer is equal to $l_s$ if the external field is zero. However, just before switching the external field is given by the coercive field $H_c$ in Eq. 12. The external field pushes the domain wall against the hard soft interface. With increasing external field the domain wall in the soft layer becomes smaller.
domain wall width can be calculated by assuming that the external field leads approximately to an effective anisotropy of the strength

$$K_{\text{eff}} = J_{s}H_{c}.$$  \hspace{1cm} (15)

The domain wall width can be calculated from the formula of the typical domain wall width of hard magnets,

$$l_{h} = \pi \sqrt[4]{A_{S}} = \pi \sqrt[4]{A_{S}} \frac{1}{K_{\text{eff}}} = \pi \sqrt[4]{\frac{A_{S}}{J_{s}H_{c}}}.$$ \hspace{1cm} (16)

In the special case when the exchange constant in the hard layer $A_{H}$ equals the anisotropy constant in the soft layer $A_{S}$ and assuming that the magnetic polarization in the hard layer $J_{H}$ is the same as the magnetic polarization in the soft layer $J_{S}$ for the required thickness of the soft layer to decrease the coercive field up to a factor of four follows,

$$l_{h} = \sqrt{2} \pi \sqrt[4]{\frac{A_{S}}{K_{H}}} = \sqrt{2} \pi \sqrt[4]{\frac{A_{H}}{K_{H}}}.$$ \hspace{1cm} (17)

Except the prefactor the above equation is in agreement with the maximum allowed thickness of soft magnetic inclusions in exchange spring bulk magnets [26]. It is worth noting that in exchange spring bulk magnets the soft magnetic inclusion should be smaller than $l_{h}$ whereas in exchange spring magnets for magnetic recording the soft magnetic layer thickness should be larger than $l_{h}$.

The length $l_{h}$ is indicated with a white circle in Fig. 9 to Fig. 11. It can be seen that $l_{h}$ well describes the critical soft layer thickness to decrease the coercive field by one quarter.

In the following the magnetic states at remanence are investigated. At remanent the full demagnetizing field of -0.5 T acts on the grain. For the calculation of the remanent state it is not appropriate to partly compensate the demagnetizing field with the exchange field. For too high demagnetizing fields the magnetization in the soft layer in the grains close to centre of a bit rotates towards the in plane direction. Laterally the magnetization of neighboring grains point in the same direction. Therefore there is no stabilizing exchange field in the up direction. Fig. 12 shows the remanent state of the magnetization of the bilayer,
when the effective field of -0.5 T acts on the bilayer. For bilayers with a soft layer exceeding 14 nm the field at remanence is sufficient to form inhomogeneous states. The coercive field is calculated for different angles $\theta$ measured between the easy axis in the hard layer and the external field. The hard layer and soft layer thickness is 7 nm. The magnetic polarization in both layers is 0.5 T. For the bilayer the coercive field and hence the energy barrier does not strongly depend on $\theta$. It can be fitted with the expression,

$$ H_c(\alpha) = H_c(0) / \cos(\theta), $$

which is commonly used to describe $H_c(\theta)$ for magnetic materials which are controlled by domain wall pinning. A nucleation is formed in the perfectly soft layer that is pushed against the interface. The angular dependence of the coercive field changes to a Stoner-Wohlfarth type behavior if the anisotropy in the soft layer is increased. For an angle between 0° and 40° the difference between Eq. (18) and the finite element calculation is less than 5%. This angular dependence is different to single phase media which can be described by the Stoner-Wohlfarth theory. For small angles $\alpha$ the change of the coercive field for exchange spring media is considerably smaller than for single phase media. This may leads to a higher signal to noise ratio for exchange spring media and may also have positive aspects on the adjacent track erasure.

9. Energy barrier of a bilayer structure

For a single domain particle the energy barrier is given by Eq. (3). The energy barrier for a bilayer structure can be calculated by assuming an infinite thick hard layer and infinite thick soft layer. An analytical solution for the energy that is required to push the domain wall from the soft layer to the hard layer was derived by Loxley et al. [20]. In the following it is assumed that the demagnetizing field is compensated by the exchange field. So no effective field acts on a grain at remanenz. At zero field the formula for the energy barrier simplifies drastically to,

$$ \Delta E_{sh} = 4F(\sqrt{AK_{hard}} - \sqrt{AK_{soft}}), $$

$$ (19) $$
where $F$ is the cross section area of the grain. Thus the energy barrier is the difference between the domain wall energy in the hard layer and the domain wall energy in the soft layer. It is important to note that for most exchange spring media (for too thick samples multidomain states are stable that lead to separated energy barriers) the total energy to reverse the particle is the energy barrier $\Delta E_{sh}$ plus the energy that is required to form a nucleation in the soft layer that is $\Delta E_s = 4F(\sqrt{AK_{soft}})$. Therefore, for the total energy barrier of exchange spring media follows,

$$\Delta E_{tot} = \Delta E_{sh} + \Delta E_s = 4F\sqrt{AK_{hard}},$$

which does not depend on the magnetic properties of the soft layer. The hard layer has to be thick enough to allow for the formation of a full domain wall. In order to calculate the energy barrier as a function of the hard layer thickness the nudged elastic band method is applied. For the calculations the soft layer thickness was fixed to 20 nm which leads to energy barriers very similar to the limiting case of an infinite thick soft layer. The grain diameter is 6 nm and the anisotropy in the hard layer is $K_{hard} = 1 \times 10^6$ J/m$^3$. Fig. 13 shows the energy barrier as a function of the thickness of the hard layer. For small hard layer thicknesses $t_h$ the energy barrier increases almost linearly as $t_h$ increases. For a hard layer thickness larger than 15 nm the energy barrier saturates. Therefore the critical thickness of 15 nm is a good choice for the hard layer thickness in exchange spring media. Thicker layers do not result in a higher thermal stability.

10. Gain in the energy barrier over coercive field

As pointed out in the last section the energy barrier of a bilayer structures is only determined by the domain wall energy in the hard layer. Therefore, a bilayer structure has the same energy barrier as a single phase media if the hard layer properties are the same (again it is assumed that no field acts on grain). For a bilayer structure with zero anisotropy in the soft layer the reduction of the coercive field is given by a factor of four. Therefore a single layer with the anistropy constant $K_1$ has the same coercive field as a bilayer structure with an anisotropy in the hard layer of $K_{hard} = 4K_1$. Since the energy barrier scales with the square root of the anisotropy constant a gain in the energy barrier of a factor of 2 can be
achieved with such a structure. A much larger gain can be obtained by increasing the number of layers. The anisotropy constant in the layer is gradually decreased. Applying this scheme the coercive field of a tri-layer structure is just $1/9$ of the anisotropy field in the hardest layer. In the limit of an infinite number of layers the coercive field can even be reduced to zero. The energy barrier does not depend on the number of layers. Details will be presented elsewhere.

11. Influence of $J_s$ on the coercive field and energy barrier

The influence of the spontaneous polarization in the hard layer and the soft layer is investigated in the following. The average spontaneous polarization, $J_{s,\text{average}} = (J_{s,\text{hard}} + J_{s,\text{hard}})/2$ of 0.5 T was kept constant. The total layer thickness is 14 nm and the soft layer thickness is 7 nm. The intergrain exchange field is 0.2 T. The demagnetizing field is evaluated as discussed in section VI.B. The shape anisotropy is neglected. In Fig. 14 the external field required to saturate the particle (saturation field) is plotted as a function of the spontaneous polarization of the hard layer. The field is applied at an angle of 7°. For $J_{s,\text{hard}} = 0.1$ T the saturation polarization $J_{s,\text{soft}} = 0.9$ T in order to fulfill $J_{s,\text{average}} = 0.5$ T. The solid line in Fig. 14 shows the saturation field taking the demagnetizing field into account. The lowest saturation field is obtained for equal values of the saturation polarization in the hard layer and the soft layer. A similar dependence can also be found if the demagnetizing field is omitted. In that approximation the coercive field can be calculated from Eq. (12). If it is assumed that the exchange constant is the same in both layers the coercive field follows from

$$H_c = \frac{(2K_{1,\text{hard}} - 2K_{1,\text{soft}})}{(\kappa J_{\text{hard}} + \kappa J_{\text{soft}})^2}.$$  \hfill (21)

It can be seen that a higher magnetization in the hard layer and a smaller magnetization in the soft layer leads exactly to the same coercive field as the opposite case. Therefore the saturation field in Fig. 14 is symmetric around $J_{s,\text{hard}} = 0.5$.

The energy barrier as a function of $J_{s,\text{hard}}$ shows a very different behavior. If the self demagnetizing field is neglected, the energy barrier of a bilayer is solely determined by
\[ \Delta E = KV_{\text{hard}} \]. In contrast to the saturation field it does not depend on \( J_{s, \text{hard}} \) in this approximation. However, if the demagnetizing field is taken into account the energy barrier will depend strongly on \( J_{s, \text{hard}} \). As pointed out in section 6.6.2 the self demagnetizing fields of both layers are almost independent and depend on the value of the spontaneous polarization in each layer. Therefore a high value of \( J_{s, \text{soft}} \) leads to a high self demagnetizing field in the soft layer and decreases the thermal stability. The influence of different \( J_s \) values on the energy barrier is shown in Fig. 15 for different strengths of the exchange field. It is interesting to note that the highest energy barrier can be obtained when the magnetization in the hard layer equals the magnetization in the soft layer. Deviations from that optimal structure lead to a reduction of the energy barrier. The energy barrier as a function of \( J_{s, \text{hard}} \) is indirect proportional to the saturation field as a function of \( J_{s, \text{hard}} \). Such a dependence which will not be observed in single phase media.

The ratio \( \Delta E/H_0 \) is mainly determined by the energy barrier. The maximum energy barrier and as a consequence the largest ratio \( \Delta E/H_0 \) is obtained for a 14 nm thick bilayer when the soft layer and the hard layer approximately have the same spontaneous polarization.

### 12. Switching times

The switching time as a function of the field strength for a bilayer structure has strong similarities to the switching time of a single phase media. For comparison we calculated the switching times for the bilayers for the same parameters as for the single layer. Now, the only difference is that each grain consists of a hard phase with a value of \( K_1 = 1 \times 10^6 \) J/m\(^3\) and a soft layer with zero anisotropy. The hard layer as well as the soft layer thickness is 7 nm. The demagnetizing field is neglected in the following calculations. Fig. 16 shows the switching time when the external field is applied one degree off the easy axis of the hard layer. Different to single phase media no fast reversal modes exist (the switching time decreases in the whole regime with increasing field strength) for all investigated field rise times. This is different when the field is applied 10° off the easy axis. Now, similar to the results for the single phase media for small external fields the switching time decreases as the field strength becomes smaller as shown in Fig 17. These fast switching modes are even more pronounced than for single phase media. For fields that are just large enough to
reverse the particles switching occurs almost 10 times faster than for fields of 2 T. It is interesting to note that for a field rise time of 0.1 ns reversal occurs within 0.1 ns to 0.2 ns. This fast reversal is almost independent on the strength of the external field. This insensitivity of the switching time on the field strength may be relevant for practical applications. For external fields applied at 45° and for extremely fast field rise times the grains can be switched with field pulses shorter than 0.025 ns. This is more than two times faster than the fastest switching in the investigated samples of single phase media.

13. Global optimization

In the previous sections the thickness of the hard layer, the soft layer thickness and the values of the magnetic polarization in both layers were varied. For all structures the energy barrier as well as the coercive field were calculated. This analysis gives a good qualitative understanding for the dependence of the coercive field and the energy barrier on these design variables. However, what is most important for magnetic recording is to find a recording media with the highest thermal stability for a given saturation field (maximum field provided by the recording head). The signal to noise ratio is not taken into account in the following optimization. For the optimization four design variables are used \( J_{s,\text{soft}}, J_{s,\text{hard}}, A_{\text{int}}, \) and the fraction of the hard layer thickness to the soft layer thickness \( t_h/t_s \). The total layer thickness is kept constant.

The value of the hard layer anisotropy constant \( K_1 \) is not a free parameter but will be used to satisfy the constrain of a constant saturation field. The demagnetizing field of each layer is taken into account in a mean field approach as discussed in section 6. The different values of the spontaneous polarization are taken into account with different demagnetizing fields in the two layers. For each set of the four design variables the saturation field \( B_0 \) is calculated first. To satisfy the constrain of a constant saturation field \( B_{\text{desire}} \) the value of the anisotropy constant in the hard layer will be adjusted iteratively. For iteration \( i \) the value of the anisotropy constant follows from the values of the last iteration as

\[
K_i = \alpha K_{i-1} \frac{B_{\text{desire}}}{B_{i-1}}.
\]
The constant $\alpha$ is a relaxation parameter which is set to 0.2 to guarantee convergence. If $B_i$ reaches $B_{\text{desire}}$ within the given tolerance the iteration stops. The four design variables together with the value of the anisotropy constant of the last iteration are used to calculate the energy barrier. Therefore the calculation of the energy barrier for a given set of design variables require various time consuming finite element micromagnetic simulations. The application of a global optimization algorithm such as simulated annealing will suffer from the high cost of each function evaluation. In general, the large number of function evaluations which are required for simulated annealing cannot be performed. A possibility to overcome this problem is to use a small number of function evaluations to train a neuronal network first. The input are the four design variables, the output which follows from hysteres loop and energy barrier calculations is the energy barrier under the constrain of the constant saturation field. The trained network is used in the following to evaluate the function evaluation for the simulated annealing process. The maximum obtained from the simulated annealing algorithm is then used as an input for a finite element simulation to calculate the energy for the specified design variables. The finite element results are used to retrain the neuronal network. This is done iteratively as shown in Fig. 19.
A free version of an algorithm which works similarly can be downloaded from Ref [15]. It bases on an evolutionary self-organizing algorithm and on a neural network [5]. The optimized bilayer and single layer structures are summarized in Table 2 for a grain diameter of 6 nm and a saturation field of 1.7 T. The angle between the average head field and the easy

<table>
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<th>$t_h/t_s$</th>
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Table 2 Compilation of the energy barrier $\Delta E(k_B T_{300})$ for different recording media with a grain diameter of 6 nm and a saturation field of 1.7 T. For a given exchange field, $B_{ex}$ (T), and a total data layer thickness, $t_{total}$ (nm), the optimal media parameters are calculated. $t_h$ and $t_s$ are the total hard layer thickness and soft layer thickness in nanometers, respectively. $K_1$ is the hard layer anisotropy constant (MJ/m$^3$). $J_s$ is the magnetic polarization (T). (*) For all structures it was found that a maximum energy barrier is obtained for full exchange between the hard layer and the soft layer. Only for thin bilayer structures ($t_{total} = 7$ nm) the exchange is reduced to 30% of the bulk value in a 1 nm thick decoupling layer.
axis is 7° in all simulations. In addition to the values shown in the table the exchange constant between the soft and the hard phase was used as a parameter. For all data sets a perfect coupling between the layers maximizes the ratio of the energy barrier to the saturation field. Only for a thin bilayer structures (\( t_{\text{total}} = 7 \) nm) the exchange is reduced to 30% of the bulk value in a 1 nm thick decoupling layer to get the highest energy barrier of 30 k\(_b\)T\(_{300}\) for that total thickness. This is in agreement with the simulations by Victora et al [33].

Fig. 20. shows some of the data of Table 2 in diagram. The energy barrier is plotted as a function of the total layer thickness for the bilayer and the single layer structure. The mean field exchange field between the grains is 0.5 T. For this exchange field it approximately compensates the demagnetizing field. Therefore only a very small effective field acts on the grain of the recording media. For zero effective field the concept of exchange spring media shows the largest benefit compared to single phase media.

With increasing total layer thickness the gain in percentage of the energy barrier for the bilayer to the energy barrier of the single layer increases. For \( t = 7 \) nm and \( t = 35 \) nm the bilayer energy barrier is by 35% and 69% larger than the single layer energy barrier, respectively. For both structures the energy barrier saturates for thicker films. The thickness at which the energy barrier saturates is larger for exchange spring media than for single phase media. Therefore an advantage of exchange spring media is that even for media thicker than 20 nm the thermal stability can be enhanced by increasing its thickness.

For a bilayer thickness of 21 nm an energy barrier of 54.5 k\(_b\)T\(_{300}\) can be obtained with the following parameters: \( J_{s,\text{hard}} = 0.55 \) T, \( \Lambda = 10^{-11} \) J/m, \( K_1 = 1.0 \times 10^6 \) J/m\(^3\), \( J_{s,\text{soft}} = 0.39 \) T. The energy barrier is about 3% higher than an optimization by hand where we used a spontaneous polarization of 0.5 T in the hard layer and in the soft layer.

As shown in Table 2 an optimized single layer with 21 nm thickness has an energy barrier of 36.3 k\(_b\)T\(_{300}\). The strong influence of the angle \( \theta \) between the external field and the easy axis as described in section 8 can be seen by optimizing the single layer for \( \theta = 1^\circ \). For \( \theta = 1^\circ \) the energy barrier is just 31 k\(_b\)T\(_{300}\).

14. Summary

The coercive field of exchange coupled bilayer structures can be decreased by a factor of four even for a soft layer thickness smaller than 15 nm with zero anisotropy. Therefore for
these structures the values of the anisotropy constant in the hard layer of a bilayer structure can be up to a factor of four larger than the value of $K_1$ for single phase media. However, this does not imply that the energy barrier of a bilayer structure is four times larger than that of a singlephase media. This is not even the case if the exchange field and the demagnetizing field compensate each other leading to zero effective field acting on one grain of the recording media. For a bilayer structure under zero applied field the energy barrier is given by $\Delta E = 4F_s \sqrt{AK_{\text{hard}}}$. The largest energy barrier which can be obtained for a single layer is given by the same formula, just the value of $K_{\text{hard}}$ is smaller by a factor of 4. Since the the energy barrier scales with the square root of the anisotropy constant the maximum gain in energy barrier achievable by exchange spring media of this structure is a factor of two. This factor of two will be decreased if the external field is applied off the easy axis of the hard layer. If the angle between the easy axis and the external field is about 7° the maximum value of $K_1$ in the bilayer structure is about a factor of three larger than that of the single phase media. This leads to a gain in the energy barrier of about 70% for the bilayer structure. A layer structure with gradually decreasing values of the anisotropy will even lead to a much larger decrease of the coercive field as it will be presented elsewhere.

The switching times in exchange spring media as a function of the field strength are similar to single phase media. For external fields applied at an angle of 45° the switching time is smaller by a factor of two compared to single phase media.

15. Acknowledgement

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16. References


Fig. 1. Maximum exchange energy and effective volume for the thermal reversal of an elongated CoCr particle as a function of the column length. The diameter is 13 nm. Beyond 20 nm the reversal mode becomes inhomogeneous. Above ~50 nm column length, the size is large enough to form a full domain wall. The maximum exchange energy as function of the length saturates and takes the value of a domain wall exchange energy.
Fig. 2. The switching time $t_s$ as a function of the field strength for different rise times $t_r$ (from 1 ps to 1 ns) of the external field. The angle $\theta$ between the external field and the easy axis is 1°.
Fig. 3. Same as Fig. 2 but the angle $\theta$ is 10°.
Fig. 4. Same as Fig. 2 but the angle $\theta$ is 45°.
Fig. 5. Schematic drawing of two grains introducing the parameters used for the calculation of the exchange field.
Fig. 6. Shows the $z$-component of the demagnetizing field for a bilayer structure with 80 nm x 80 nm. The soft layer thickness as well as the hard layer thickness is 7 nm. $J_{s,\text{soft}} = 2$ T and $J_{s,\text{hard}} = 0$. 

$J_{s} = 2$ T

$J_{s} = 0$ T

$B_{z}$

1.8 T

-0.18 T
Fig. 7. Energy barrier of one grain of a single phase recording layer. The value of $K_1 = 3 \times 10^5 \text{ J/m}^3$. The energy barrier is calculated for the grain black colored in the right inset. Both, the demagnetizing field and the exchange field are taken into account.
Fig. 8. The demagnetization curve of a bilayer structure for different thicknesses of the soft layer are shown. The soft layer thickness varies from 6 nm to 22 nm. The hard layer thickness is 20 nm.
Fig. 9. The coercive field of a bilayer structure as a function of the soft layer thickness for a value of the anisotropy constant in the hard layer of $K_{\text{hard}} = 0.25 \times 10^6 \text{J/m}^3$ is shown. The hard layer thickness is 20 nm. The white dot indicates $l_h$ which is given by Eq. 17.
Fig. 10. Same as Fig. 9 but $K_{\text{hard}} = 1.0 \times 10^6$ J/m$^3$. 
Fig. 11. Same as Fig. 9 but $K_{\text{hard}} = 4.0 \times 10^6$ J/m$^3$. 
Fig. 12. The remanent state of the bilayer structure for different soft layer thicknesses is shown. The magnetization is shown along a line perpendicular to the film plane. After saturation in the up direction, the magnetization configuration under the influence of the interaction field was calculated.
Fig 13. Energy barrier as a function of the hard layer thickness. The soft layer thickness is 20 nm. Grain diameter is 6 nm, $K_{\text{hard}} = 1 \times 10^6$ J/m$^3$. No effective field acts on the bilayer.
Fig. 14: The saturation field as a function of \( J_s \) in the hard and soft layer. The average \( J_s = 0.5 \) T. The plot starts with \( J_{s,\text{hard}} = 0.1 \) T and therefore \( J_{s,\text{soft}} = 0.9 \) T. The value of the anisotropy constant in the hard layer is \( K_{\text{hard}} = 1.0 \times 10^6 \) J/m³. The exchange field is 0.2 T. (dotted line) The demagnetizing fields in both layers are omitted. (solid line) The demagnetizing field in the hard layer and the soft layer are taken into account as described in section 6.2.
Fig. 15: The x-axis is the same as in Fig. 14, however, instead of the saturation field the energy barrier is plotted for two different values of the intergrain exchange.
Fig. 16: The switching time $t_s$ as a function of field strength for different rise times $t_r$ (from 1 ps to 1 ns) of the external field for an exchange spring recording media. The hard layer thickness is equal to the soft layer thickness 7 nm. The anisotropy in the hard layer is $1 \times 10^6 \text{ J/m}^3$. The angle $\theta$ between the external field and the easy axis is $1^\circ$. 
Fig. 17: Same as Fig. 16 but the angle $\theta$ is $10^\circ$. 
Fig. 18: Same as Fig. 16 but the angle $\theta$ is 45°.
Train a neuronal network with a small set of FE simulations

Use the trained network for simulated annealing

New optimal design variables (approximation)

Perform FE sim. with new set of design variables to calculate $\Delta E$

Train neuronal network with new set of design variables and $\Delta E$

Fig. 19: Flow chart of the global optimization approach. A neuronal network is used together with a simulated annealing approach for global optimization.
Fig. 20: Maximum energy barrier as a function of the total layer thickness of a bilayer and a single layer. For the global optimum search a constant saturation field of 1.7 T is assumed. The angle between the easy axis and the external field is 7° for both the single layer and the bilayer. For every data point the global optimization routine determines the optimal value of $J_{s,\text{hard}}, J_{s,\text{hard}}$, the fraction hard layer thickness to soft layer thickness and the exchange between the hard layer and the soft layer. The value of $K_{1}$ in the hard layer is determined by the constrain of a constant saturation field.