Magnetic storage device with improved temporal stability

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(October 31, 2018)

The current efforts to fabricate non-volatile magnetic recording media with a high areal density is deteriorated by the increasing temporal instability of the stored information. If the stored energy per magnetic particle competes with the thermal energy, spontaneous magnetic reversal processes may occur. Deposition of the magnetic particles on top of an antiferromagnetic substrate will increase its energy barrier due to the exchange coupling between the two subsystems. For this the magnetic moments of the antiferromagnet in the vicinity of the magnetic particle have to deviate from their undisturbed arrangement. This disturbance vanishes within a few lattice constants. In the framework of a classical spin model we calculate the spin arrangements and the resulting energy barriers for typical systems.

PACS: 75.10.Hk, 75.75.+a, 85.70.Li

A high areal density and low noise of non-volatile magnetic recording media is achieved by use of nanostructured thin films consisting of weakly coupled ferromagnetic grains deposited on a nonmagnetic substrate. The two stable magnetic states, which determine the information of a single bit, are separated by an energy barrier which is roughly proportional to the size of a single grain. Currently much effort is being expended on the increase of the areal bit density [1]. However, the decreasing bit size and thus the decreasing energy barrier reduces the temporal stability of the stored information. Thermal agitation may prompt spontaneous magnetic reversal processes resulting in a possible loss of the stored information, therefore limiting the achievable areal density. Technical requirements demand a lost of maximal 5 % of the stored information at ambient temperatures over 10 years [2]. Considering the known magnetic recording media with high magnetic anisotropies and coercivities such as Co/Pt multilayers [3], and the current compound density growth rate, this stability limit is expected to be reached within a few years. To achieve high areal densities of magnetic recording media accompanied by proper thermal and temporal stabilities, we propose that the reversibility of magnetic recording media accompanied by proper thermal and temporal stabilities, we propose that the required energy barrier can be enhanced by depositing the ferromagnetic grains or clusters on top of an antiferromagnetic substrate.

The characteristic time to overcome the energy barrier is estimated in the framework of the Arrhenius-Néel statistical switching model [4]:

\[ \tau = \tau_0 \exp \left( N \cdot \frac{\Delta E}{k_B T} \right). \]

(1)

\( N \) is the number of atomic magnetic moments in the cluster, \( T \) the absolute temperature, and \( k_B \) the Boltzmann constant. The energy barrier per cluster atom \( \Delta E \) results usually from the magnetic lattice anisotropy and the magnetic dipole coupling. \( \tau_0^{-1} = 10^9 \) to \( 10^{12} \) sec\(^{-1} \) is the attempt frequency to overcome the energy barrier. The atomic magnetic moments \( \mu_{at} \) of a cluster are assumed to be ferromagnetically ordered (collinear magnetization), the cluster can thus be viewed to carry a single giant magnetic moment \( M = N \cdot \mu_{at} \) (Stoner-Wohlfarth particle) [5]. The above mentioned temporal stability requirement [6] yields the ratio \( N \cdot \Delta E/k_BT \sim 43 \) at the least.

If a ferromagnetic (FM) cluster is placed on top of an antiferromagnetic (AFM) substrate, the FM and AFM subsystems are coupled by a (usually short range) interface exchange interaction. If due to this interface coupling the magnetic moments of the AFM substrate close to the FM cluster are allowed to deviate from their equilibrium (undisturbed) AFM arrangement, the total energy of the system decreases and a net magnetic coupling between the two subsystems emerges. Then the energy barrier of the FM cluster between its two stable states increases, and an enhanced temporal stability of the stored information is obtained. In the following we will calculate the energy barriers for typical coupled FM – AFM systems.

A classical Heisenberg Hamiltonian with localized magnetic moments (spins) \( \mu_i \) on an fcc(001) lattice is considered. The magnetic moments are subject to the exchange interaction \( J_{ij} \) between nearest neighbors, the lattice anisotropy \( K_i \), the long range magnetic dipole coupling, and the external magnetic field \( B \) (Zeeman energy):

\[
E = -\frac{1}{2} \sum_{\langle i,j \rangle} J_{ij} \mu_i \mu_j - B \sum_i \mu_i - \sum_i K_i \cos^2 \Phi_i + \frac{1}{2} \sum_{i \neq j} \frac{1}{r^5} \left[ \mu_i \mu_j r^2 - 3(r \mu_i)(r \mu_j) \right].
\]

(2)

The FM and the AFM subsystems are characterized by the exchange couplings \( J_{\text{FM}} \) and \( J_{\text{AFM}} \), the anisotropies \( K_{\text{FM}} \) and \( K_{\text{AFM}} \), and the magnetic moments \( \mu_{\text{FM}} \) and \( \mu_{\text{AFM}} \). For these quantities typical values are taken into account. In addition the FM and the AFM subsystems are coupled by the interface exchange interaction \( J_{\text{FM–AFM}} \). This coupling also causes the unidirectional anisotropy (exchange bias) observed for extended FM-AFM interfaces [7]. The distance between a spin pair is given by \( r = |r| = |r_j - r_i| \). For simplicity the spins are
allowed to rotate only in the plane of the substrate face, with Φ, the in-plane angle of the i-th spin.

The FM cluster with a finite vertical and lateral extension is placed on top of an AFM substrate. Due to the magnetic interactions the spins of both the FM cluster and the AFM substrate may deviate from their undisturbed directions (easy axes). Only in the vicinity of the FM cluster the AFM spins will deviate markedly from their equilibrium directions. Thus, for our calculations a finite region of the AFM substrate close to the FM cluster will be considered, in which the AFM spins are allowed to move. Its extension has to be chosen in such a way that the calculated energy barrier per spin and other quantities do not change if its range is enlarged. This disturbed AFM region is embedded in an undisturbed extended AFM substrate.

The energy barrier ΔE is calculated from the magnetic reversal of the FM cluster. An external magnetic field B with sufficient strength is applied, forcing the FM cluster magnetization to rotate from one to its other easy direction. For given coupling parameters and magnetic field angle ΦB the directions Φi of each spin of the FM cluster and the disturbed AFM region are varied until the total energy E(ΦB), equation (5), of the coupled system is minimal. This energy minimum needs not necessarily be the global minimum. The Zeeman energy has to be subtracted from E(ΦB). The corresponding energy barrier ΔE is determined from the difference between the minimum and the maximum of E(ΦB).

In Fig.1 a typical behavior of E(ΦB) in units of K/spin, diminished by the Zeeman energy, is shown as a function of the magnetic field angle ΦB. A square FM cluster with a single atomic layer and a lateral extension of about five lattice constants is assumed. The range of the disturbed AFM region is chosen to be 12 lattice constants in lateral and 10 lattice constants in vertical direction. For the coupling constants and magnetic moments of the FM cluster we use JFM = 160 K, KFM = −0.5 K, μFM = 0.6 μB, and for the AFM system JAFM = −130 K, KAFM = 0.5 K, μAFM = 2.5 μB. These values are typical for a bulk Ni ferromagnet and a NiO antiferromagnet [8]. The interface coupling is chosen to be JFM–AFM = 7 K in this example. As can be seen from the full line in Fig.1, this value of JFM–AFM refers to an energy barrier ΔE which is twice the energy barrier ΔE0 of the decoupled case JFM–AFM = 0 (dotted line). ΔE0 is determined mainly by the lattice anisotropy KFM of the FM cluster. A doubling of ΔE increases the characteristic time of the magnetic reversal and thus the temporal stability by a factor e2 ~ 8.

In Fig.2 we show the resulting energy barrier ΔE as a function of the interface coupling JFM–AFM. Four different values for the exchange interaction JAFM of the AFM substrate are assumed, referring to different substrate materials. As can be estimated by a simple calculation, ΔE increases almost quadratically with JFM–AFM. Furthermore, for the same value of JFM–AFM the energy barrier is the smaller the stronger JAFM. A stronger deviation of the AFM spins from their equilibrium arrangement increases the magnetic binding energy to the FM cluster.

![FIG. 1. Magnetic energy E(ΦB) in units of K/spin as a function of the interface coupling JFM–AFM.]()
that this interface needs not necessarily be very flat, an interface coupling will be present also for rough interfaces. Also, the interface coupling can be controlled by adding magnetic or nonmagnetic impurities or a spacer layer between the FM clusters and the AFM substrate. An oscillating interlayer coupling between ferromagnetic layers as a function of the spacer layer thickness has been observed for a number of multilayer systems [9].

The enhanced energy barrier due to $J_{FM-\text{AFM}}$ is an interface effect, since only the FM cluster spins close to the interface to the AFM substrate experience the interlayer coupling. The FM cluster spins not located near the FM/AFM interface are subject only to the lattice anisotropy and the magnetic dipole coupling, as for a cluster located on a nonmagnetic substrate. Thus, assuming the same number of spins in the FM cluster, the contribution of the interface coupling to the energy barrier is smaller for a compact than for a flat island, since the resulting interface area is smaller for the compact island. Thus the relative contribution of the interlayer coupling to the energy barrier per spin will decrease for a decreasing interface-to-volume ratio of the cluster. By controlling the size as well as the shape of the FM clusters the energy barrier $\Delta E$ can be varied according to technical requirements.

The reading and in particular the writing process of the recording media must be performed independently bit by bit. This infers that the FM grains which carry different informations must be placed within such a distance that the writing process of a single bit does not interfere with the state of its neighboring bits. From our calculations we find that the disturbance of the AFM spin arrangement decays rapidly within a few lattice constants. Both the degree of disturbance and its range become larger if the interface coupling to the FM cluster increases.

The energy barrier $\Delta E$ per spin of the FM cluster should be large enough to guarantee the required temporal stability. On the other hand, $\Delta E$ must not be too large in order to allow for a controlled magnetic reversal by an external magnetic writing field with appropriate strength and within a short switching time. This implies an upper limit for $\Delta E$ and thus for the interface coupling.

The above calculations have been performed at zero temperature. A finite temperature $T$ can be considered, if a free energy expression with temperature dependent coupling coefficients is applied, resulting in a temperature dependent energy barrier $\Delta E(T)$. These coefficients can be calculated e.g. by a molecular field theory [10]. Usually a finite temperature facilitates the reversal of the cluster magnetization. For an increasing temperature the characteristic time to overcome the energy barrier (switching time) becomes smaller, cf. equation (1).

Note that for temperatures above its magnetic ordering temperature a single FM cluster cannot be viewed as a Stoner-Wohlfarth particle, resulting in an upper limit of the operation temperature of such granular systems. The coupling to the extended AFM system will improve the magnetic ordering of the FM cluster at finite tempera-

Acknowledgement: Numerous discussions with H.-D. Hoffmann are gratefully acknowledged.

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