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Critical fields of an exchange coupled two-layer composite particle

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Abstract

High-density recording systems require magnetic bits with perpendicular easy axis and large magnetocrystalline anisotropy to guarantee thermal stability. However, the large magnetic fields up to 10 T for the reversal of magnetization cannot be afforded by conventional write heads. Therefore, composite exchange coupled spring systems of soft and hard magnetic layers may be used to reduce the switching field. In this case the reversal of magnetization in general takes place in two steps: a nucleation process in the soft layer and a depinning process for the displacement of the domain wall at the phase boundary of the soft and the hard magnetic layer. The nucleation and depinning fields are determined on the basis of the continuum theory of micromagnetism. It is shown that the nucleation fields decrease according to a $1/L^2$ law with increasing thickness L of the soft layer and the depinning field of the charged Néel wall may be reduced by factors of 3–6 in comparison with the ideal nucleation field of the hard magnetic phase. One-step rectangular hysteresis loops are obtained for thicknesses of the soft layer smaller than the exchange length of the magnetostatic field.

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1. Introduction

Non-volatile magnetic recording has become one of the most active fields of modern magnetism [1–4]. Whereas the conventional magnetic recording uses particles magnetized in-plane with respect to the substrate, high-density recording requires so-called perpendicular magnetization of the particles in order to achieve recording densities of Tbit/in^2. This change of the type of magnetic particles raises a number of problems concerning the optimization of their storage abilities to be discussed in this paper. Optimum magnetic recording properties are obtained if the individual particles correspond to single domain particles with easy axes oriented perpendicular to the planar substrate. Furthermore, the switching field should be of the order of 0.5–1.0 T and the switching time should lie in the subns region. Highly anticorrosive materials are preferred with a blocking temperature for the transition to superparamagnetism above 200 °C and guaranteed lifetimes of the bits above 10 years. These conditions may be fulfilled by using uniaxial materials with large magnetocrystalline anisotropy and a suitable geometry of the particles. In general, large magnetic anisotropies satisfy most of the conditions, however, lead to large reversal fields which so far cannot be afforded by the available write heads. In order to guarantee thermal stability as well as suitable coercivity it has been proposed to use composite particles [5–10]. These are composed of a magnetically soft and a magnetically hard ferromagnetic part. In such a composite particle the reversal of magnetization takes place by a nucleation process in the magnetically soft phase if the film thicknesses are thick enough so that a full domain wall fits inside. The reversal of the hard phase may take place by the displacement of the domain wall which exists near the phase boundary and is situated mainly in the soft magnetic phase. Here we have to consider two configurations. If the easy axes of the particles are oriented parallel to the substrate the domain wall corresponds to a Bloch wall and if the easy axes are oriented perpendicular to the substrate the domain wall corresponds to a so-called charged Néel wall. The pinning of Bloch walls at planar barriers has been treated

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previously for narrow and wide barriers $D\langle\rangle\delta_B$ (δ_B: wall width) [11–14]. Also the case of atomistically narrow phase boundaries has been treated recently [15]. The basis for these investigations is the continuum theory of micromagnetism. So far the case of Néel walls has not been treated. It will be the topic of this paper to derive the depinning field of a Néel wall at a planar phase boundary which separates two phases of different magnetic material parameters. Micromagnetic investigations of exchange coupled layers have been published by several authors [16–18] where the effects of remanence enhancement and of demagnetization processes have been investigated. Furthermore, it should be noted that in several papers dealing with composite nanocrystalline materials it has been shown that the coercive field decreases with increasing amount of the soft magnetic phase and increasing grain diameter [19–22].

2. Model of a composite particle

Fig. 1 shows the spin configurations at zero magnetic field and after nucleation of the reversed state in the magnetically soft layer. The magnetic material parameters, spontaneous polarization, magnetocrystalline anisotropy constant and the exchange stiffness constant are denoted as J, K_1 and A. The magnetization $\boldsymbol{M}$ follows from $\boldsymbol{J}=\mu_0\boldsymbol{M}$ (μ_0: vacuum permeability). The magnetically soft layer will be denoted by an index I and the hard layer by an index II. The magnetic field $\boldsymbol{H}_{ext}$ is applied inversely to the original orientation of $\boldsymbol{J}$ which is aligned parallel to the perpendicular easy directions of the composite particle. The rotation of $\boldsymbol{J}$ is described by the angle φ between $\boldsymbol{J}$ and the positive easy direction. The inversely oriented magnetic field in the following is counted as negative.

3. Micromagnetic equations

In order to determine the critical fields for the reversal of magnetization in the soft and hard magnetic phase we start

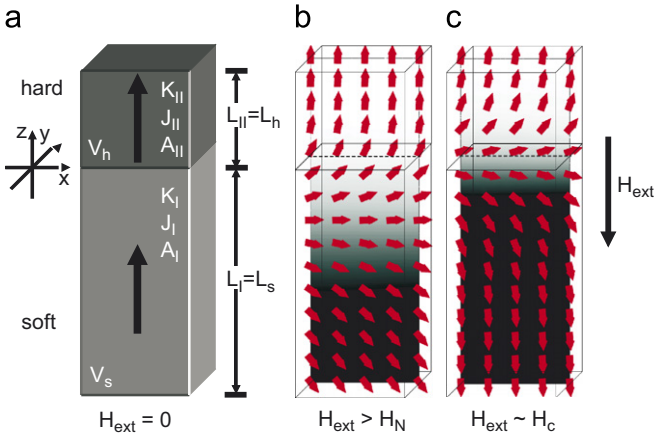

Fig. 1. Model of a composite particle: (a) Definition of material properties and magnetization arrangement at zero field. (b) Magnetization configurations after nucleation in the soft magnetic layer at $H_{ext}\sim H_N$ and for $H_{ext}\leqslant H_{dp}$.

from the magnetic Gibbs free energy of the spin configuration under an applied magnetic field. The reversal of magnetization starts at low fields in the magnetically soft phase. If the reversal of magnetization is more or less complete at some distance from the phase boundary a charged Néel wall is formed in the soft magnetic phase near the phase boundary due to the exchange coupling with the hard magnetic phase. With increasing field the Néel wall is pushed against the phase boundary and at a certain critical field penetrates fully this barrier and reverses spontaneously the magnetization in the hard magnetic particle. For calculation of the magnetic Gibbs free energy first Poisson's equation

$$\Delta U = \operatorname{div}\boldsymbol{M} \tag{1}$$

has to be solved with the magnetostatic field defined as

$$\boldsymbol{H}_s = -\nabla U, \tag{2}$$

where U denotes the magnetostatic potential. In the case of a one-dimensional problem where all fields depend only on the z-coordinate Poisson's equation writes

$$\frac{dH_{z,i}}{dz} = -M_i\frac{d}{dz}(\cos\varphi(z)), \tag{3}$$

where we have introduced the z-component of the spontaneous magnetization $M_{z,i}=M_i\cos\varphi$. The one-dimensional treatment of the magnetostatic field is possible for films extending in x- and y-direction to infinity and also represent a good approximation if the lateral extensions are larger than the so-called exchange lengths [14]. Integration of Eq. (3) under the above mentioned conditions gives

$$H_{z,i} = -M_i\cos\varphi, \tag{4}$$

where the index $i=$ I refers to the soft and the index $i=$ II to the hard magnetic phase. With the magnetostatic stray field energies

$$\phi_{s,i} = -\frac{1}{2}J_{z,i}\cdot H_{z,i} = \frac{1}{2}M_iJ_i\cos^2\varphi \tag{5}$$

the total magnetic Gibbs free energy writes with $i=$ I or II for uniaxial materials

$$\begin{aligned}\phi_t = &\int_{L_s}^{0}\left\{A_I\left(\frac{d\varphi}{dz}\right)^2 + K_I\sin^2\varphi - H_{ext}J_I\cos\varphi\right.\\ &\left.+\frac{1}{2}M_IJ_I\cos^2\varphi\right\}dz\\ &+\int_{0}^{L_h}\left\{A_{II}\left(\frac{d\varphi}{dz}\right)^2 + K_{II}\sin^2\varphi - H_{ext}J_{II}\cos\varphi\right.\\ &\left.+\frac{1}{2}M_{II}J_{II}\cos^2\varphi\right\}dz,\end{aligned} \tag{6}$$

where A_i denote the exchange constants and K_i the first anisotropy constant. Minimization of ϕ_t with respect to φ leads to the following micromagnetic equations in