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Nucleation and wall motion in graded media

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Magnetization reversal in graded magnetic-recording media and its effect on the areal density are investigated by model calculations. By choosing suitable solid-solution materials it is conceptually straightforward, though practically challenging, to achieve arbitrarily low write fields. The writing process involves both the nucleation of reverse domains and their propagation along elongated particles. The performance of the medium is optimized for pinning and nucleation fields of comparable size, and the two fields can be tuned by adjusting the length of the elongated particles (pillars) and the anisotropies of the hard and soft ends. However, the write-field reduction negatively affects the areal density, and there remains a trade-off between write field and bit size. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2835483]

Magnetic-recording media require high thermal stability (large energy barriers E_a) and easy writability (small coercivity H_c). Inhomogeneous nanostructures have recently attracted much attention in magnetic recording, because they combine low writing fields with high magnetic anisotropy.[1–3] In other words, two- or multiphase hard-soft materials can be used to improve the writability of recording media by reducing the coercivity without negatively affecting the thermal stability. An explicit proposal for *continuous* media is to exploit that a reduction of the domain-wall energy gradient $d\gamma/dx$ makes media easier to write.[4] Figure 1 shows a typical nanostructure. Simplifying somewhat, the soft end of the pillar (bright) ensures a low write field, whereas the hard end at the bottom (dark) provides the thermal stability of the stored information.

Continuous anisotropy profiles may be realized in solid solutions with spatially varying composition, such as $Nd_{1-x}Sm_xCo_5$, where the anisotropy reaches zero close to $x=0$,[5] and gas-phase interstitially modified $Sm_2Fe_{17}N_x$, where the end members Sm_2Fe_{17} and $Sm_2Fe_{17}N_3$ are magnetically soft and hard, respectively.[6,7] Another possibility is to prepare magnets such as FePt magnets with varying degree of $L1_0$ order, realized, for example, by a temperature gradient during heat treatment. The production of appropriately graded pillars is certainly challenging, but there is no fundamental objection against materials with graded anisotropy.

Coercivity H_c tends to increase with the uniaxial anisotropy K_u, but there is no simple relationship between coercivity and volume-averaged anisotropy. It has been known for many years that continuous and discontinuous reductions of the local anisotropy reduce the coercivity, and this reduction has been a major problem in permanent magnetism.[8–11] Only recently it has been tried to positively exploit the coercivity reduction.[1–3] Magnetization reversal in graded columns (pillars) involves two mechanisms, the nucleation of a reverse domain and the pinning of the domain wall in the pillar. To realize a low coercivity, one must reduce both the nucleation field and the pinning field. Trivially, this is achieved by choosing a soft magnet, where the uniaxial anisotropy constant K_u is small and both the nucleation field ($H_N \sim 2K_u/\mu_0 M_s$) and the pinning field ($H_P \sim dK_u/dz$) are close to zero. However, soft magnets are not suitable for magnetic recording, because magnetically stored information loses thermal stability with decreasing anisotropy.

Nucleation refers to the global or local instability of the original magnetization state,[7,8,12] whereas pinning means that the domain-wall motion is inhibited due to inhomogeneities.[7,13–15] Pinning is the main source of coercivity in strongly inhomogeneous materials, such as steel, where carbon causes a pronounced martensitic lattice distortion of the bcc iron lattice. By comparison, nucleation determines the coercivity of nearly perfect magnets.

To realize a low coercivity in graded magnets, one must reduce *both* the nucleation field and the pinning field. Figure 2 shows the meaning of the two mechanisms in graded pillars. Nucleation is facilitated by making one end of the pillar soft, but the domain wall must penetrate into the hard region. This costs domain-wall energy and yields, for an abrupt anisotropy profile, a strong pinning force (pinning field). The pinning field is essentially zero in structurally homogeneous pillars, where the domain-wall energy is independent of the

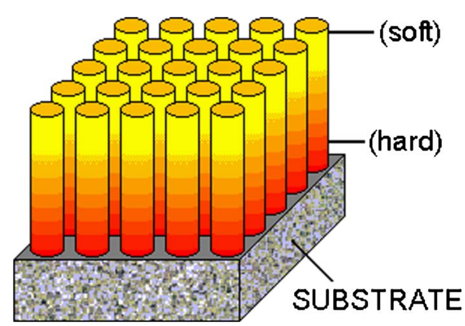

FIG. 1. (Color online) Graded medium with perpendicular geometry. The substrate is in the *x*-*y* plane and the pillars grow in the *z* direction.

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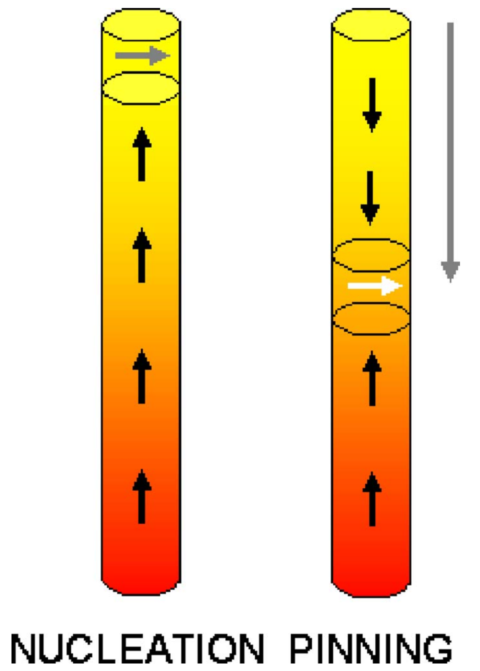

FIG. 2. (Color online) Nucleation and pinning in elongated nanoparticles (schematic). The easy magnetization axis is parallel to the symmetry axis of the pillar and the white arrow indicates a domain wall.

position z along the pillar. A feature of thin wires or pillars is that the shape anisotropy can be incorporated into the magnetocrystalline anisotropy $K_u(z)$, so that $K(z)=K_u(z)-\mu_0 M_0^2/4$ and the problem becomes essentially one dimensional.[16] The nucleation field obeys the equation[11]

$$A\nabla^2 m + K(z)m = 2\mu_0 M_0 H_N m, \tag{1}$$

where A is the exchange stiffness. Throughout this paper we focus on anisotropy inhomogeneities $K(z)$; magnetization and exchange-stiffness inhomogeneities have a less pronounced impact on the magnetization reversal.[11] The pinning field is obtained from

$$H_p = \max(d\gamma/dx)/2\mu_0 M_s, \tag{2}$$

where $\gamma=4(AK)^{1/2}$ is the domain-wall energy.[11,13] Equation (2) epitomizes the write-field reduction in graded media.

Figure 3 shows numerically determined pinning forces and nucleation modes for a typical profile of $K(z)$. However,

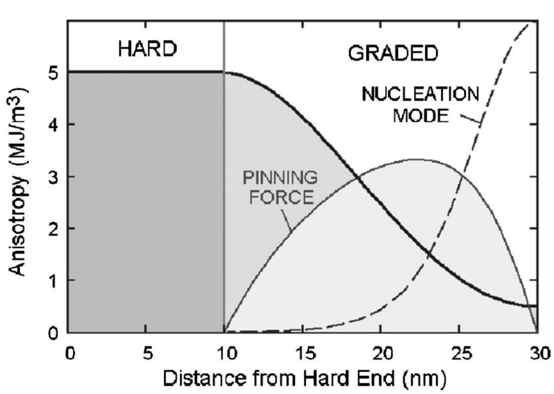

FIG. 3. Spatial character of pinning and nucleation in graded pillars (arbitrary units). The nucleation occurs at the soft end, but the pinning field (pinning force) remains quite large in the middle of the pillar.

for our purposes, it is convenient and sufficient to use an anisotropy profile with analytical solutions for H_N and H_P. Consider a pillar containing a hard end of length L_h and a part of length L_s with graded anisotropy, similar to the region from 10 to 30 nm in Fig. 3. The anisotropy of the hard end is K_h, whereas that of the graded part decreases to K_s at the soft end. In the graded part, we first assume a parabolic anisotropy profile so that $dK(z)/dz=0$ at the soft end.

It is well known that the nucleation modes for parabolic anisotropies $K\sim z^2$ are Gaussian,[8] and for lengths L_s larger than the Bloch-wall widths $\delta_h=\pi(A/K_h)^{1/2}$ one obtains the nucleation field

$$H_N = H_s + H_h\delta_h/\pi L_s \tag{3a}$$

and the pinning field

$$H_P = H_h\delta_h/\pi L_s. \tag{3b}$$

Here $H_h=2K_h/\mu_0 M_0$ and $H_s=2K_s/\mu_0 M_0$ are the anisotropy fields of the hard and soft ends, respectively.

The second model replaces the parabolic part of length L_s by two segments of length $L_s/2$. The segment located at the soft end has the anisotropy K_s, whereas the segment bridging the hard and soft ends has an anisotropy that varies linearly from K_s to K_h. In this case, the nucleation field changes to

$$H_N = H_s + H_h\delta_h^2/\pi L_s^2 \tag{4a}$$

and pinning field is

$$H_P = H_h\delta_h\frac{\sqrt{H_h/H_s}}{\pi L_s}. \tag{4b}$$

Comparison of Eqs. (3a), (3b), (4a), and (4b) shows that relatively small changes in the anisotropy may change the behavior of the pillars quite drastically.

Magnetization reversal (switching) is realized by the pinning or nucleation field, whichever is higher. In Eqs. (3a), (3b), (4a), and (4b), the switching field decreases with increasing length of the soft region. This is not surprising, because the pinning field is essentially given by the anisotropy gradient, and because the nucleation process in the soft end is barely affected by distant hard regions. The soft-phase anisotropy field H_s and the length L can be used to tune the pinning and nucleation fields. However, there is no point in designing media that combine high nucleation fields with low pinning fields or high pinning fields with low nucleation fields—both combinations amount to an unnecessary switching-field increase. The first combination, nucleation-controlled switching, means that the low pinning field of the gradient region is not exploited, whereas the second combination, pinning-controlled reversal, means that the small anisotropy of the soft end does not translate into complete reversal.

In Eqs. (3a) and (3b), the nucleation field is always larger than the pinning field, irrespective of H_h, H_s, and L_s. This does not mean that the writing reduces to the nucleation of a reverse domain at the soft end of the wire, because the calculations leading to Eqs. (3a), (3b), (4a), and (4b) assume a homogeneous magnetic field. Figure 3 shows that the pinning—or, more precisely, depinning—occurs somewhere

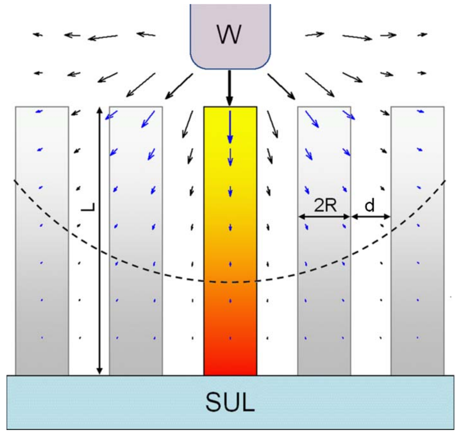

FIG. 4. (Color online) Field distribution for a finite-length dipole write head (W) in the presence of a SUL. The SUL helps to focus the field but does not prevent the field from rapidly decreasing toward the middle of the particle. The arrows show the field created by the write head.

in the middle of the pillar. For example, Eqs. (3b) and (4b) correspond to respective distances of L_s and $L_s/2$ from the soft end. This is a major consideration, because write heads create local rather than global fields. Figure 4 illustrates the writing process in a continuously graded columnar medium.

Even if we neglect interactions between pillars, which are likely to create additional complications, the write head in Fig. 4 is unable to cause the switching of individual columns. To address an individual soft end, the pole dimensions of the head must be very small, comparable to the center-to-center distance $D=2R+d$ of the columns. If the writing were restricted to the top ends of the columns, where the write field is large and well focused, high densities of the order of $1/(R+d/2)^2$ could be achieved. However, since the actual writing is realized in the middle of the pillars, this requires rather high write fields at the soft end. More importantly, the writing in the middle of one column affects neighboring columns. In Fig. 4, the range of the diffuse writing is indicated by the dashed line. This focus limitation leads to a reduction of the areal density of about $1/D^2$ for single-bit or "single-pillar" writing by a factor of order $(2R+d)^2/L^2$. The soft underlayer (SUL) helps to focus the field but does not yield a significant write-field localization.

A strong reduction of D is not possible due to well-known thermodynamic limitations. Note that using pillars of large hard-phase volume $V_h=\pi R^2(L-L_s)$ and exploiting $\xi k_B T=K_h V$ ($\xi \approx 50$) is not an option, because the thermal stability of thin wires[17] is determined by $\xi k_B T = 4\pi R^2 (A K_h)^{1/2}$ and K_h is limited to about $10\ \mathrm{MJ/m^3}$ or $10^8\ \mathrm{ergs/cm^3}$.

Equations (3a) and (3b) yield the rough estimate $H_h \delta_h / \pi L_s$ for the write field. Since $\delta_h = \pi\ (A/K_h)^{1/2}$ and $H_h = 2K_h/\mu_0 M_s$, we obtain an areal density of order $AD=1/L_s^2$ or

$$AD = \frac{\mu_0^2 M_0^2 H_w^2}{4AK_h}. \quad (5)$$

Equation (5) shows that small write fields are paid for by a reduced areal density. Somewhat different expressions are obtained for other switching mechanisms. Note that Fig. 1 is not the only possible realization of a graded medium. One may also consider laterally structured media and particles where a soft core (or a soft shell) reduces the coercivity. However, in all cases, very small coercivities correspond to large real-space feature sizes, which limit the areal density.

In conclusion, we have investigated how magnetization processes in graded recording media with columnar structure affect the write field and the areal density. It is necessary to distinguish between pinning and nucleation, and an optimized performance is expected for structures where the pinning and nucleation fields are of comparable magnitude. By using long pillars, the write field can be made arbitrarily small, but there is trade-off between achievable areal density and write field, even in the absence of interactions. The reason is that small write fields must push the domain wall deep into the pillars, where the write field is relatively weak and also quite diffuse, deeply reaching into neighboring pillars and inhibiting single-bit writing.

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