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Switching of composite media by wall propagation

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Using simple scaling arguments, we calculate the external field required to propagate a domain wall from the soft to the hard phase in a composite media. In the absence of the external field the domain-wall energy is lower in the soft phase, resulting in an energy barrier between the hard and soft phases. It is shown that as the external field increases the domain-wall energy in the soft phase also increases, and there is a corresponding wall energy reduction in the hard phase, resulting in the lowering of the energy barrier. The switching field is obtained as the field, which equalizes the domain-wall energies in both phases, reduces the wall barrier to zero, and leads to wall propagation and reversal. The calculation allows identification of field dependent anisotropies and wall widths of the two phases, which become equal at the reversal field. The reversal field is found to linearly depend upon the intrinsic anisotropy difference and inversely on the sum of magnetization of the two phases. Moreover, the reversal field is found to be independent of the volume of the two phases. An attempt at exhaustive comparison with experiments is made. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2177389]

INTRODUCTION

Increasing magnetic storage densities has led to the storage industry focusing on high-anisotropy magnetic grains such as FePt and Co_xPt for thermal stability. The external field H_{ext} available from the traditional heads has not kept up with the reversal field value of these high-anisotropy grains, with $H_c \gg H_{ext}$. To overcome this, the storage industry is developing heat assisted magnetic recording (HAMR), where the magnetic grains are heated for reduction of the effective H_c. However, most of the H_c reduction happens only near T_c, which is typically higher than the boiling point of the lubricant on the disk surface.[1]

A potential solution of this problem is the use of composite media, in which two different magnetic materials with different anisotropies are exchange coupled.[2] Most of the understanding of composite media in the context of media design has been obtained in terms of coupled coherent rotation of both the hard and soft materials.[2]

Recently it has been shown that, in contrast to the coherent rotation consensus, reversal is noncoherent.[3,4] Reversal is initiated in the soft phase, and a domain wall is formed at the interface between the hard and soft phases. This domain wall then propagates through the hard phase under the action of an external field.

The two important fields associated with the reversal process are H_{n1} domain-wall nucleation field in the soft phase and H_{dw} domain-wall propagation field from the soft to the hard phase. The switching field H_{sw} is given by $\max(H_{n1}, H_{dw})$.[3] Understanding of both H_{n1} and H_{dw} and their dependence on the phase volumes is essential for the design of media especially in demarcating the boundaries of dominance of H_{n1} and H_{dw}.

In this paper a simplified theory of H_{dw} using simple scaling arguments is presented. It is justified by a more complete treatment based on the calculus of variation presented in Ref. 3. There are two wall solutions, 1 and 2, with stationary energies [Fig. 1(a)], one mostly in the soft phase and the other mostly in the hard phase. In the absence of the external field their energies are given by $E_1 = 4\sqrt{AK_{u1}}$ and $E_2 = 4\sqrt{AK_{u2}}$, where A is the exchange stiffness and K_{u1} and K_{u2} the anisotropies of the two phases. This gives rise to an energy barrier of $E_2 - E_1 > 0$ at the interface and to an entrapment of the wall in the soft phase where wall energy is lower [Fig. 1(a)]. Solution 2 in the hard phase is at the top of the barrier and hence unstable. It will be shown below that in the presence of the external field the energy of the domain wall in the soft phase increases and that in the hard phase reduces, consequently reducing the barrier. At $H_{ext} = H_{dw}$, the wall energies in both phases are the same and the domain wall propagates from the soft to hard phase leading to complete reversal [Fig. 1(b)].

WALL PROPAGATION FIELD

In this section, the expression of the domain-wall propagation field H_{dw} is obtained using a simple scaling argument of domain-wall energy.

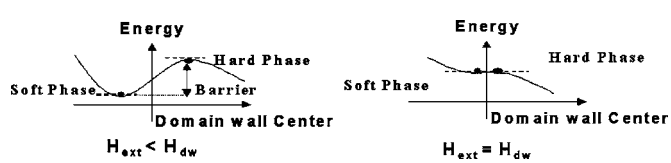

FIG. 1. Schematic of domain-wall energy barrier.

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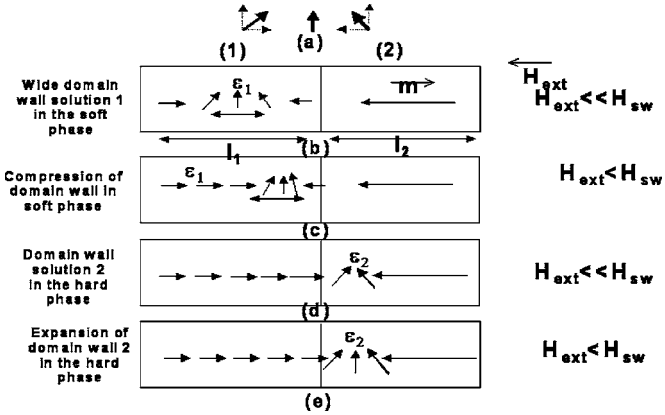

FIG. 2. Schematic of equilibrium domain-wall width with increasing H_{ext}.

In the presence of an external field a free domain wall would move along the field direction without any change in its width. In the case of a trapped domain wall the field acts as an anisotropy field and compresses its width, as shown in Fig. 2. In the case of composite media the hard phase entraps the wall at the phase boundary and the wall width is consequently compressed due to the external field. In the presence of the external field the total energy of the soft phase is the summation of Zeeman, anisotropy, and exchange energy and is given by,

$$E_1 = (\alpha\varepsilon_1 - l_1)m_1 H_{ext} + 2\varepsilon_1 K_{u1}/\pi + 2\pi A/\varepsilon_1, \tag{1}$$

where ε_1 is the wall width, K_{u1} is the anisotropy, H_{ext} is the external field, m_1 is the magnetization, A is the exchange stiffness, and l_1 is the thickness of the soft phase.

The numerical factors in front of the anisotropy and exchange term are chosen to give the correct values of wall energy and width in the absence of field. Here, α is a constant which can be obtained when the angular dependence of the Zeeman energy density is integrated within the wall limits. The value of α will be obtained later [Eq. (3)]. The first term of Eq. (1) represents the Zeeman energy of the region of length $\varepsilon_1 - l_1$ which is not occupied by the wall. The Zeeman energy in the domain wall is near zero because for a given spin in the wall there is another spin with the opposite spin component which cancels it [Fig. 2(a)]. This assumption is strictly true only when the domain wall is entirely contained in the hard or the soft phase.

The condition $\partial E_1/\partial\varepsilon_1 = 0$ gives the equilibrium wall width $\varepsilon_{eq_1} = \pi\sqrt{A/K_{u1'}}$ and the wall energy $E_{eq1} = 4\sqrt{AK_{u1'}}$, where $K_{u1'} = K_{u1} + \alpha\pi m_1 H_{ext}/2$ can be thought of as an effective anisotropy of medium 1 in the presence of the external field. As is clear from this formula, with increasing external field the effective anisotropy of medium 1 increases, leading to an increase in the energy of the domain wall and a reduction in the domain-wall width.

We now consider the other wall solution, located mostly in the hard phase. As the field increases, the spins near the interface start reversing. The domain wall is pinned because the unreversed spins away from the interface pin the domain wall. As the field increases, the domain wall expands reducing the energy of the phase because more spins align along the external field [Figs. 2(d) and 2(e)]. The energy of the hard phase in the presence of the external field and the domain wall is given by $E_2 = (l_2 - \alpha\varepsilon_2)m_2 H_{ext} + 2\varepsilon_2 K_{u2}/\pi + 2\pi A/\varepsilon_2$.

Going through the same analysis for the hard phase, one can see that in the presence of the external field the equilibrium wall energy and width are given by $E_{dw_{2eq}} = 4\sqrt{AK_{u2'}}$ and $\varepsilon_{eq_2} = \pi\sqrt{A/K_{u2'}}$, where $K_{u2'} = K_{u2} - \alpha\pi m_2 H_{ext}/2$. Note that increasing external field reduces the effective anisotropy $K_{u2'}$ of the hard phase. This contrasts with the treatment by Kneller and Hawig[5] where the effect of the field on the hard phase is completely ignored.

For $H_{ext} < H_{dw}$, we have $E_{eq1} < E_{eq2}$, equivalent to a potential barrier stopping the wall at the interface. As the external field approaches the switching field the domain-wall energy in 1 becomes equal to the domain-wall energy in 2, $E_{eq1} = E_{eq_2}$, and the domain wall slides from 1 to 2 leading to a reversal of the entire grain. This leads to the expression of the wall propagation field,

$$H_{dw} = 2(K_{u2} - K_{u_1})/(\alpha m_1 + \alpha m_2)\pi. \tag{2}$$

Note that the domain-wall energy equality as the external field reaches the switching field leads to the equality of the effective anisotropies of the two phases at the switching field, $K'_{u1} = K'_{u2}$. Thus the *switching field* can be thought of as an *external field* which *equalizes* the *effective anisotropies* of the two phases, consequently also equalizing the *effective domain-wall widths*.

Note that H_{sw} increases as the difference in the intrinsic anisotropies of the hard and soft phases increases [see Eq. (2)]. In the limit $K_{u1} = K_{u2,}$ where both phases are of the same material, the energy barrier to domain-wall sliding from 1 to 2 is zero, as expected. Another salient feature of Eq. (2) is that the switching field is inversely proportional to the sum of the magnetizations of the two phases. This indicates that the external field acting on both phases contributes to the lowering of the domain-wall propagation barrier. Thus, from the perspective of switching field, the composite media acts like a medium, with effective anisotropy equal to the difference of the intrinsic anisotropies and with an effective magnetization equal to the sum of the intrinsic magnetization. Unlike in earlier works,[2,6] H_{dw} is predicted [Eq. (2)] to be independent of the phase volumes.

In the limit $K_{u1} \to 0$ and $m_1 \to 0$, where the soft phase is eliminated, the switching field should reduce to H_{k2}. Applying these limits to Eq. (2) leads to $\alpha = 1/\pi$, giving

$$H_{sw} = H_{dw} = 2(K_{u2} - K_{u1})/(m_1 + m_2). \tag{3}$$

An important point to note is that in the limit $m_{1\to 0}$ and $m_{2\neq 0}$, or $m_{2\to 0}$ and $m_{1\neq 0}$, the exact form $H_{dw} = 2(K_{u2} - K_{u1})/(\sqrt{m_1} + \sqrt{m_2})^2$ given by the more abstract variational theory[3] agrees with Eq. (3).

Next we consider the limit of maximum difference between the anisotropies of the two phases, i.e., when $K_{u1} \to 0$ (infinitely soft phase). In this limit, H_{dw} of Eq. (3) reduces to $H_{k2}/(1+r)$, where $r = m_1/m_2$, and the domain-wall

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TABLE I. Switching field $H_{sw}=H_{dw}$. All field values are in tesla.

Soft	Hard	H_{k2}	r	$H_{k2}/(1+r)$	Expt. H_{dw}
Co	Sm–Co	3.4 (RT)	2.6	0.9	0.4[a]
Co	Sm–Co	7.3 (25 K)	2.6	2.0	1.0[a]
Fe	Sm–Co	3.4 (RT)	3.1	0.8	0.7[a]
Fe	Sm–Co	7.3 (25 K)	3.1	1.8	1.5[a]
Fe	Nd–Fe–B	0.31	1.7	0.1	0.04[b]
FeRh	FePt	1 (250 °C)	1.12	0.5	0.3[c]

[a]Reference 6.
[b]Reference 7.
[c]Reference 2.

energy barrier is reduced only due to the Zeeman energy, as expected.

SUMMARY AND COMPARISON WITH EXPERIMENTS

In Table I we compare $H_{dw} \approx H_{k2}/(1+r)$ to various sets of experimental data. This expression for H_{dw} is justified because the soft layers (Fe, Co, etc.) used in the experiments have much lower coercivity than the hard layer. As stated before, the switching field is given by $\max[H_{n1}, H_{dw}]$. As the soft-phase length scale is increased, H_{n1} reduces and the switching field will be dominated by H_{dw}.[3,6] Since H_{dw} is independent of the phase volumes the switching field becomes independent of the soft-phase length scale when $H_{sw} = H_{dw}$. For most of the pairs of materials reported in Table I this is around 10 nm. We find that in most cases there is a fair agreement between the theoretical and experimental H_{dw}.

The total grain length is constrained at about 20 nm for perpendicular magnetic recording (PMR) media. This can raise concerns regarding fitting of the compressed domain wall in the soft layer. As we have seen earlier, when the external field is equal to H_{dw} the compressed domain-wall width in the soft phase would be roughly equal to the domain-wall width of the hard phase. This leads to the fact that the grain dimension has to be around twice that of the hard-phase domain-wall width. For realistic material combinations of composite media the high-anisotropy hard-phase materials like Sm–Co and FePt have domain-wall widths of about 8–10 nm, allowing media design within the limits of PMR. This is also reflected in H_{dw} becoming independent of the soft-phase length scale at around 10 nm as discussed above.

In conclusion, we have presented a simple theory for understanding the energy barrier and its field dependence for the design of composite media. This theory does not require calculus of variations. The limitation of the simple theory is that the energy of each of the wall solutions is calculated [Eq. (1)] as if the wall were mostly contained in its own phase, with little penetration of the interface. This is a crude approximation because the domain wall does penetrate both the phases (see Ref. 3). The predicted H_{dw} is higher than the experimental one. In Kneller-Hawig[5] theory, where the field acts only on the soft phase, this discrepancy would be much larger.

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