Simple model for thin ferromagnetic films exchange coupled to an antiferromagnetic substrate

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(Received 9 March 1987; accepted for publication 9 June 1987)

The exchange field H_{ex} transferred from a thick antiferromagnetic substrate to a thin exchange coupled ferromagnetic film is shown to reach a limiting value no matter how large the exchange coupling is. The limit is due to domain-wall formation in the antiferromagnet. Numerical results based on a simple model for the interface are presented and compared to experimental results.

The exchange interaction leading to various magnetic ordering phenomena is a short-range interaction; that is, one can successfully explain magnetic order by considering next and maybe next-nearest neighbors only. A striking application of this arises if one deposits a thin film of a ferromagnet, say Co, on top of an antiferromagnet, say CoO.[1] At the interface, the exchange interaction $J\,\mathbf{S}_1\cdot\mathbf{S}_2$ favors parallel alignment of the Co spins $\mathbf{S}_1$ and $\mathbf{S}_2$ in the ferro- or antiferromagnet, respectively. If the antiferromagnet has a uniaxial anisotropy and has been brought into a single-domain state, the ferromagnet is completely magnetized in the direction of the anisotropy of the antiferromagnet if its own anisotropy is either in the same direction or sufficiently small. One now has to apply a magnetic field H_{ex} in order to reverse the magnetization M of the ferromagnet (F) even when F has no anisotropy of its own. H_{ex} is called the effective exchange field.

It is a challenge to both theorists and experimentalists to understand H_{ex} quantitatively in terms of the atomic microstructure of the interface, particularly since H_{ex} has found interesting applications, e.g., in magnetoresistive sensors.[2] With JS^2 the energy per pair of Co atoms and $1/a^2$ the number of pairs per unit area (a is the lattice parameter), one might naively expect that $H_{ex} = 2JS^2/a^2Mt$, where t is the thickness of the ferromagnetic film. However, this formula can yield H_{ex} values that are too large by orders of magnitude if one assumes bulk values for the exchange parameter J. Various phenomena like contamination, pinholes, or roughness of the interface have been invoked to understand this discrepancy.[3] It is the purpose of this communication to show that H_{ex} can indeed be low due to poor interface coupling but will also be low in general for more fundamental reasons. Our model yields the above *naive* formula for small exchange coupling $2JS^2/a^2$ at the interface, yet its special feature is that $H_{ex}tM$ reaches a limit no matter how large $2JS^2/a^2$ is. The physical reason for this limit is that a domain wall can be built in the *antiferromagnet* reversing the spins at the interface. The energy required per unit area of this domain wall is $2\sqrt{AK}$, where A and K are the exchange stiffness and crystalline anisotropy in the antiferromagnet, respectively. This leads to the more realistic equation $H_{ex}tM = 2\sqrt{AK}$ valid for any strong interface coupling as we shall show below.

The present simple model is illustrated in Fig. 1. The infinitely thick antiferromagnet (AF) is assumed to have a uniaxial anisotropy in the z direction. This simple assumption may have to be changed when definitive experimental evidence becomes available showing more complex anisotropies in antiferromagnetic films. Spins of only one sublattice are depicted. At a distance ξ at the interface, a ferromagnetic film of thickness t follows. The F thickness t is chosen to be much smaller than the thickness of a domain wall in the ferromagnet. Hence one can assume that the spins in the ferromagnet all include the same polar angles β with the z axis.

The spins in the last layer of the AF include the angle α with the z axis. If $\alpha \neq 0$, a tail of a domain wall extends into the AF. The total magnetic energy of this interface is

$$\delta^* = 2\sqrt{AK}\,(1-\cos\alpha) + A_{12}/\xi\,[1-\cos(\alpha-\beta)] + K_F t\cos^2\beta + HMt(1-\cos\beta). \quad (1)$$

The first term is the energy of the tail of a domain wall extending into the bulk of the AF according to Zijlstra,[4] the second term is the familiar exchange energy with A_{12} the exchange stiffness at the interface, the third term is the an-

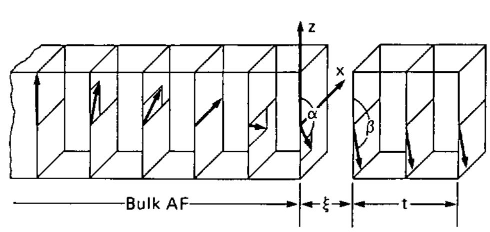

FIG. 1. Magnetic model for the interface of a thin ferromagnetic film on a thick antiferromagnetic substrate. The uniaxial anisotropy of the antiferromagnet is along the z axis. The figure depicts a situation in which an external magnetic field is applied opposite to z and in which the exchange coupling across the interface with thickness ξ is positive. The spins of only one sublattice of the antiferromagnet are shown.

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 0021-8979/87/193047-03$02.40

isotropy energy in the ferromagnet with anisotropy constant K_F, and the last term is the magnetostatic energy. The energy in units of $2\sqrt{AK}$, which is the energy per unit surface of a 90° domain wall in the AF, is

$$\delta = (1 - \cos\alpha) + \lambda\,[1 - \cos(\alpha - \beta)] + \mu\cos^2\beta + \kappa(1 - \cos\beta). \quad (2)$$

The interface exchange $\lambda = A_{12}/\xi 2\sqrt{AK}$ can be <0 or >0 depending on whether parallel or antiparallel coupling of the spins is favored. The anisotropy $\mu = K_F t/2\sqrt{AK}$ can also be <0 or >0 depending on whether the easy axis of the ferromagnet is parallel or perpendicular to the z axis, respectively. With $\kappa(1-\cos\theta)$ where $\kappa = HMd/2\sqrt{AK}$, the external field is applied along the z axis. If one wants it to lie along the x axis, the last term must read $\kappa(1 - \sin\beta)$ (see Fig. 1).

Magnetization curves (MC's) of the ferromagnetic film are calculated from Eq. (2) by finding the angles α_0 and β_0 for which δ is at minimum. $M\cos\beta_0$ is the magnetization of the ferromagnet along z. For $\lambda = 0$, one obtains the familiar MC's found by Stoner and Wohlfarth[5]; if $\lambda \neq 0$, the MC's are modified by the AF.

The limiting cases $\lambda \ll 1$ and $\lambda \gg 1$ can be readily obtained by considering that for $\lambda \ll 1$, α will be very small, whereas for $\lambda \gg 1$, $(\alpha - \beta)$ will be very small. Expression (2) can then be approximated as follows, neglecting constant terms:

$$\mu\cos^2\beta - (\kappa + \lambda)\cos\beta \quad \text{for } \lambda \ll 1,$$
$$\mu\cos^2\beta - (\kappa + 1)\cos\beta \quad \text{for } \lambda \gg 1.$$

Both expressions are formally identical to the energy of a uniaxial ferromagnet in an external field. The critical fields can be easily derived in a coherent rotation model, which predicts in both cases a square MC's of coercivity 2μ. The loop will be, however, shifted on the κ axis of $-\lambda$ for $\lambda \ll 1$ and -1 for $\lambda \gg 1$. Hence we obtain

$$tH_{ex} = -[(A_{12}/\xi)/M] \quad \text{for } \lambda \ll 1 \quad (3a)$$
$$tH_{ex} = -2(\sqrt{AK}/M) \quad \text{for } \lambda \gg 1. \quad (3b)$$

More detailed information on the range of applicability of the present simple approach is obtained by numerically calculating MC's from Eq. (2).

The energy δ is computed for every pair of angles α and β in steps of 3° and the relative minima and maxima are determined as a function of the applied field κ. MC's are constructed on the basis of the coherent rotation model according to which a discontinuous reversal will take place when a given relative minimum disappears and becomes a relative maximum.[5] Figure 2 shows MC's in the easy and hard directions for $\mu = -0.25$ and $\lambda = 0.25$, 1.0, and 4.0. The MC's of the interface layer of the AF are also shown in the same figure.

The following observations can be made about the easy-axis hysteresis loops:

(1) At $\lambda = 4$ the steady-state situation is virtually reached. The loop is shifted from the origin by ~ 1, which is the limiting value of the exchange field according to Eq. (3b). The coercivity is ~ 0.5, i.e., 2μ, which is also expected from Eq. (2) for large values of λ.

(2) Peculiar shapes of the MC's with asymmetrically rounded edges occur for λ close to 1, e.g., $\lambda = 0.5$ and 1. Whereas the reversal of the remanent magnetization is started by an irreversible jump for every value of λ, the return to the remanent state is preceded, for λ close to 1, by a region of reversible rotation. MC's are square for λ much smaller and much larger than 1.

(3) For $\lambda > 1$ the reversal of the F magnetization is accompanied by a total reversal of the interface AF magnetization. This means that for $\lambda > 1$ 180° domain walls are created in the AF.

The exchange coupling affects the hard-axis MC's in two ways:

(a) The sharp onset of the saturation which is found for

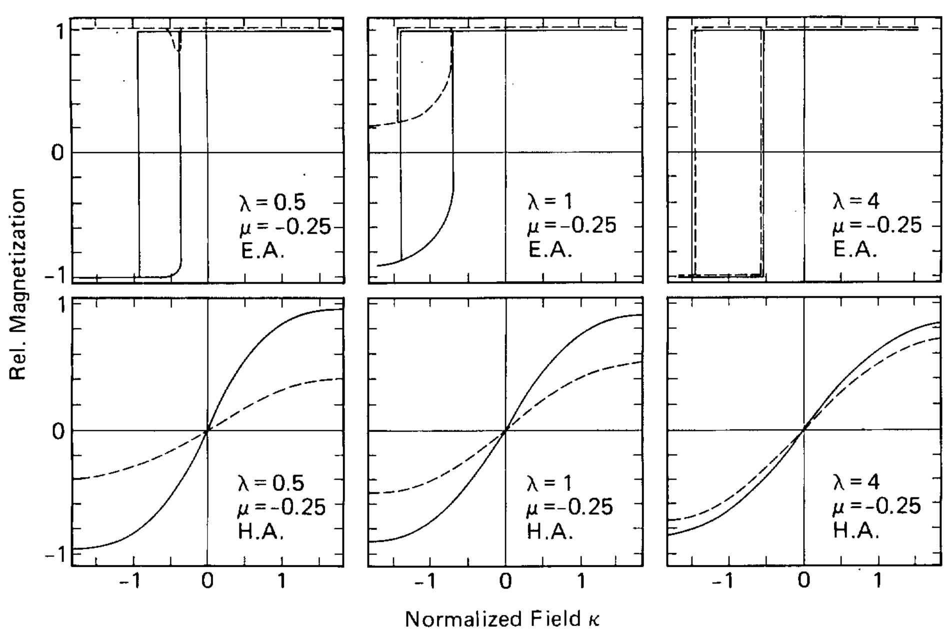

FIG. 2. Magnetization curves for $\mu = -0.025$ and $\lambda = 0.5$, 1.0, and 4.0. The solid lines represent the magnetization of the ferromagnetic layer; the dashed lines the magnetization of the interface antiferromagnetic plane (slightly displaced in the three upper panels for clarity). The magnetic field is applied along the ferromagnetic easy axis (E.A.) for the three upper panels, and in the hard axis (H.A.) in the three bottom panels.

$\lambda = 0$, see Ref. 5, is replaced by an asymptotic approach, which becomes slower for increasing values of λ.

(b) The initial susceptibility χ is lowered by the exchange coupling but reaches a stable value for large λ.

In contrast to the easy-direction case, the behavior of AF does not change dramatically at $\lambda = 1$. Increasing λ simply reduces the angular lag in the magnetization of F and AF.

Figure 3 summarizes the main characteristics of easy- and hard-axis MC's as a function of λ for $\mu = -0.25$. The most important result of this calculation as can be seen in Fig. 3 is that the exchange field can only become smaller than 1 when λ is smaller than 1.

The coercivity shows a broad minimum between $\lambda \sim 0.25$ and 4 and has otherwise the constant value 2μ, which is the coercivity of the free F. Our model cannot account, therefore, for the increased F coercivities or the shrinkage of the hysteresis loops which are observed in AF-F systems.[6] It is, however, conceivable that domain walls created in AF could be pinned by imperfections giving rise to irreversible changes of the interface. The effects of AF on coercivity can then be explained in the spirit of the model proposed by Néel,[7] which postulates irreversible sublattice magnetization changes in AF.

The dashed curve in Fig. 3 represents M_s/χ which is the saturation magnetization of F divided by the initial susceptibility in the hard direction, which can be interpreted as an effective anisotropy field. M_s/χ also becomes insensitive to λ, at $\lambda \sim 5$, reaching the constant value of $1.5 = 1 + 2\mu$ which is the sum of the exchange field plus the intrinsic anisotropy field of F.

Experimental results are available for a variety of AF-F systems including Permalloy on MnFe, MnFeNi alloys, and α-Fe_3O_3; further Ni on NiO and Co on CoO.[6] The model should apply to all of these cases provided that the AF is thicker than the width of a domain wall, $\pi\sqrt{A/K}$.

As an example let us consider Permalloy on MnFe. Typical for the experimental results is that the center of the easy loops or the slope of the hard-axis MC shifts as the interface is made free of oxygen and contamination,[8] but then a limit of the exchange shift or the slope, respectively, occurs whatever the improvements in the preparation of the interface are. It would be interesting to decide whether it is the interface coupling that actually reaches a limit or if domain-wall formation sets the limit. To this end, knowledge of A_{12}/ξ, K, and A is required.

The anisotropy in a MnFe film was recently determined with a new technique[9] yielding $K \sim 1.3 \times 10^5$ erg/cm^3. The exchange stiffness can be estimated to be $A \sim 3 \times 10^{-7}$ erg/cm. The energy of a 90° domain wall in MnFe is therefore $2\sqrt{AK} \sim 0.4$ erg/cm^2.

We notice that exchange coupling between individual lattice layers in bulk MnFe corresponds to $\lambda \sim 30$; therefore, the condition $\lambda > 1$ might seem realistic for good interfaces; however, in the sandwich examined in Ref. 9 this was not the case since the interface coupling was only $A_{12}/\xi \sim 0.07$ erg/cm^2, giving $\lambda \sim 0.18$ i.e., well below the threshold for domain-wall formation. This is probably the case for most experiments dealing with this interface as can be seen from the following considerations. Using the above values of A and K and 780 emu for the Permalloy magnetization, formula 3(b) yields $tH_{ex} \sim 50\,000$ Oe Å as a limiting value for MnFe/Permalloy interfaces. For the particular sample studied in Ref. 9 this product was only $\sim 10\,000$ Oe Å; however, even better interfaces[3,8] are about a factor of 2 below the given limit, pointing out that the interface coupling is indeed weak, i.e., $\lambda < 1$.

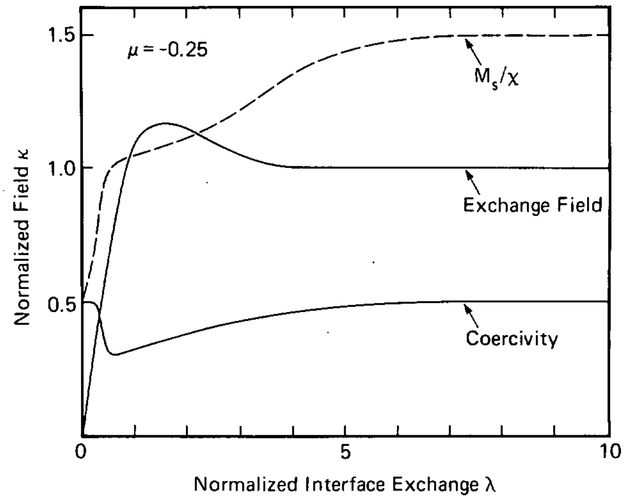

FIG. 3. Main characteristics of the magnetization curves as a function of the exchange parameter λ for a fixed ferromagnetic anisotropy $\mu = -0.025$. The solid curves are derived from E.A. hysteresis loops and are the loop half width (coercivity) and the loop displacement (exchange field) in terms of the normalized field K. The dashed curve is derived from the H.A. magnetization curves and is the field K obtained by dividing the saturation magnetization M_s by the initial susceptibility.

It is interesting to note that a more realistic description of interfacial effects such as roughness have been treated in a more sophisticated model recently proposed by Malozemoff[10] but do not change significantly the overall conclusion reached by both approaches, namely that domain-wall energy is a critical parameter.

We would like to thank C. Tsang and A. Malozemoff for very helpful discussions.

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