RAPID COMMUNICATIONS

PHYSICAL REVIEW B, VOLUME 63, 060404(R)

Influence of interface coupling on spin-flop critical fields in ferromagnet-antiferromagnet coupled systems

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(Received 5 July 2000; published 18 January 2001)

A fundamental parameter for coupled ferromagnet/antiferromagnet systems is the effective exchange coupling at the interface between the two materials. This parameter, however, remains difficult to measure because the exchange-bias also depends on the interface roughness and the degree of noncompensation in the antiferromagnet top layer. We investigate, theoretically, a different quantity, the spin-flop transition in the antiferromagnet. We find that the shift in the spin-flop field, H_{sf}, depends critically on the exchange coupling at the interface and is only weakly dependent on the noncompensation. Thus we suggest a method for determining the magnitude and sign of the interface coupling from magnetization measurements. We also discuss how the spin-flop field depends on the thickness of the antiferromagnet.

DOI: 10.1103/PhysRevB.63.060404 PACS number(s): 75.70.Cn, 75.50.Ee, 75.25.+z

Coupled films of ferromagnetic (F) and antiferromagnetic (AF) materials have received much attention recently due mainly to the application of these structures in spin-valve devices. The two major effects of this coupling on hysteresis curves are enhancement of the coercivity and a shift of the curve-exchange bias. Although this phenomenon was observed over 40 years ago,[1] there is still difficulty in theoretically relating the observed bias to the actual interface coupling.[2–9] There are two reasons for this; first, it is difficult to directly measure the interface coupling and second, the effective field due to the interface coupling is theoretically several orders of magnitude larger than field bias observed from measuring hysteresis curves. Hence, a method for determining the interface coupling from another measurement is desirable.

Although one recent theoretical model[4] predicts exchange bias in compensated interfaces, others[5–8] rely on some small noncompensation of spins at the interface and describe the bias field as a function of interface roughness.[10] As a result, many experimental studies rely on careful characterization of the interface roughness in their attempts to extract interface coupling from the measured bias effect.[8,11] We present here a method for determining both the sign and magnitude of interface coupling in F/AF bilayers by measuring an effect, the spin-flop field, which is fairly independent of the degree of noncompensation. Our study is motivated by some recent experimental measurements connecting the spin-flop transition with exchange biasing.[12]

In this paper we use a simple model to determine the spin structure in F/AF bilayers as a function of the applied field, temperature, film thickness, interface coupling, and the degree of noncompensation. Our model is quasi-one-dimensional, with one spin representing a layer in the F film and two spins (*a* and *b*) per layer in the AF film. The geometry and effective exchange interactions are shown in Fig. 1. Similar models have been used with good success to describe a variety of magnetic multilayer structures.[13–15]

The exchange coupling and anisotropy values were all modeled in terms of effective fields. The values were chosen to represent real materials. H_{ff}, the effective field from a F spin on a neighboring F spin, was set to 550 T in order to yield a T_C equal to that of Fe. The in-plane exchange field in the AF, H_{ab1}, and the nearest-plane exchange H_{ab2} were set to 30 and 19 T, respectively, to yield a T_N of about 67 K—near that of MnF_2. Note that Fig. 1(a) also shows the interface couplings H_{fa} and H_{fb} (the F to AF ''a spin'' coupling and the F to AF ''*b* spin'' coupling). Noncompensation at the interface was modeled by using slightly different values for H_{fa} and H_{fb}.

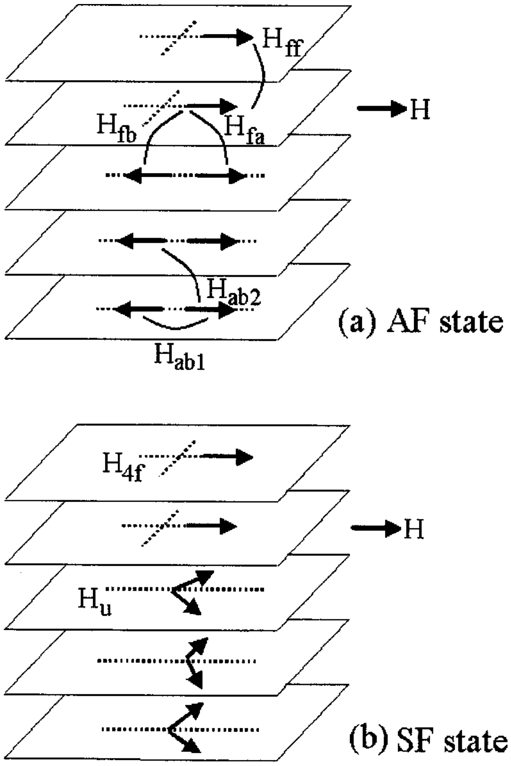

FIG. 1. The basic spin structure and the effective field parameters used in our model. H_{ff}, H_{ab1}, and H_{ab2} model the exchange fields within the ferromagnet or the antiferromagnet. H_{fa} and H_{fb} model interface exchange—noncompensation is modeled by H_{fa} not equal to H_{fb}. The easy axes for each material is shown as a dashed line. (a) shows the antiferromagnetic state found at lower fields while (b) shows the spin-flop state found for very high fields.

0163-1829/2001/63(6)/060404(4)/$15.00

The easy axis of the AF is along the x axis, parallel to the applied field. The magnitude of the uniaxial anisotropy field in the AF, H_u, was selected to be 0.45 T; this created H_{sf} equal to about 8 T at 10 K. This is near the value for MnF_2 ($H_{sf}=9.5$ T at 10 K). The magnitude of the fourfold anisotropy field in the F was selected as $H_{4f}=0.055$ T and an easy axis of the F lies parallel to the uniaxial anisotropy in the AF.

The spin configuration at a given temperature is found through a local mean-field method. Each spin is characterized by an in-plane angle (no out-of-plane canting was possible) and by a ''thermal magnitude.'' We randomly selected a spin, calculated the effective field on that spin, and then reset the spin in the direction of the effective field. This lowers the energy of the system. Next, we computed a thermal magnitude for the spin using the Brillouin function, which is a function of the magnitude of the effective field and the temperature. This process was repeated on the order of 10 000 times per spin for each value of applied field and temperature. The program included an algorithm for detecting phase changes and adding iterations at those transitions to improve accuracy. At phase transitions the number of iterations necessary can increase substantially and can be on the order of one million iterations per spin.

The method described above is essentially an energy minimization scheme. One can also find the equilibrium spin positions by a dynamical method where the spins are allowed to precess in time according to their equations of motion while large damping forces them to their equilibrium positions. For the exchange biasing problem, these two methods give different results because an instability in the configuration found by the dynamical method is not allowed in the energy minimization scheme.[5,6] For our problem of characterizing the spin-flop field, however, there is no equivalent instability and we have checked that the two methods give the same results.

Figure 1 shows the key magnetic configurations, the antiferromagnetic phase and the spin-flop phase. At all applied fields 0.2 T and higher, the F spins are essentially locked in the direction of the applied field, while the AF spins lie nearly parallel and antiparallel as shown in Fig. 1(a). At H_{sf}, the AF spins rotate to roughly perpendicular to the applied field and cant slightly in the direction of the field. This spin flop phase is illustrated in Fig. 1(b). The change in configuration causes a distinct step increase in the total magnetization.

We note that at very low fields we find a configuration where the AF spins are aligned with the easy axis in the antiferromagnet and the F spins are perpendicular to this direction. This is the typical structure found for compensated surfaces when looking at the exchange biasing issue.[4–6] In exchange biasing, one typically looks at hysteresis curves for small external magnetic fields, and the biasing and coercive field are sensitive to small deviations from compensation. Furthermore, the exchange biasing generally requires a certain thickness for the antiferromagnetic film before the effect occurs. In contrast, the high-field measurements proposed here are relatively insensitive to deviations from compensation (as we shall see) and also the effect becomes stronger as the antiferromagnetic film is reduced in thickness.

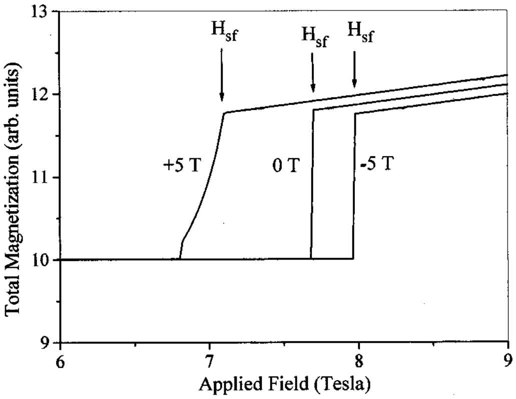

FIG. 2. Example of magnetization curves used to determine H_{sf}. These calculations were for 10 F layers and 15 AF layers. The numbers by the curve indicate the interface coupling fields. The AF surface is completely compensated.

We determined H_{sf} from total magnetization curves such as those in Fig. 2. While looking at curves for increasing and decreasing fields, we observe a small hysteresis (hundredths of T) in the phase transition that has been predicted by other models.[14] We chose to measure H_{sf} using increasing fields and defined the critical field as the top of the step (positions shown in Fig. 2). For the large-coupling curve, the curved portion before the phase change is caused by the top AF layer, which remains in a spin-flop state for all fields greater than about 0.2 T.

Our study of the effect of noncompensation at the interface yielded a surprising result. We used H_{fa} greater than H_{fb} by 0, 1, and 5 % and found that H_{sf} was nearly the same in all cases. There was some small motion in the phase transition field (less than 2%). In contrast, the exchange bias field is likely to change by over 100% over this same range of parameters. The primary difference was the shape of the transition, which was less abrupt for larger interface spin imbalance.

We have used noncompensation to model one of the effects of interface roughness. Of course, this roughness can have other consequences not included in our model. One such consequence would be the creation of domains in the ferromagnet. This could be a problem for small applied fields, as is typical in loop-shift measurements. In our model, however, we are concerned with large magnetic field associated with the spin-flop transition. In this case the ferromagnetic is certainly saturated and single domain.

Figure 3 shows the dependence of H_{sf} on interface coupling strength (H_{fa}, was set equal to H_{fb} so we have a completely compensated surface). The plot shows data for AF thicknesses of 15 and 30 layers. In both cases, the F thickness was 10 layers. Note that the variation is more pronounced in the case of the thinner AF. Near zero coupling, the effect on H_{sf} is nearly linear; similar coupling magnitudes raise or lower H_{sf} by similar amounts. For small antiferromagnetic interface coupling, the F layer produces an effective field on the interface of the AF that is antiparallel to

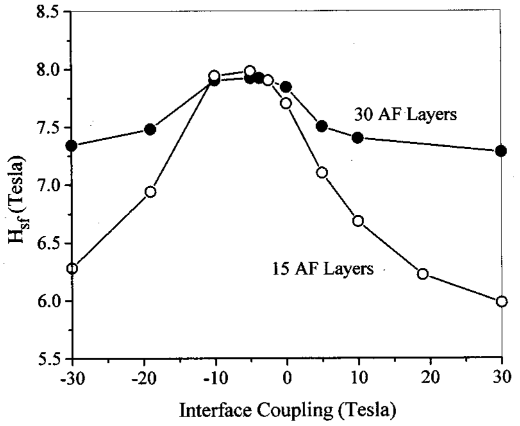

FIG. 3. Dependence of H_{sf} on interface coupling for two thicknesses of the AF film. The ferromagnetic film thickness was kept constant at 10 layers. The AF surface is completely compensated.

the applied field. For small ferromagnetic coupling, the effective field on the AF is aligned with the applied field. Thus, antiferromagnetic interfacial coupling increases H_{sf}, and ferromagnetic interface coupling decreases H_{sf}. As a result, a measurement of the spin-flop field for an uncoupled AF film and for the same AF film coupled to a ferromagnet can give both the sign and magnitude of the effective interface exchange coupling.

For larger antiferromagnetic coupling, another effect takes over. Layer 1 in the AF becomes strongly canted away from the applied field due to the strong interface coupling effective field. Both the *a* and *b* spins in layer 1 push the *a* and *b* spins in layer 2 of the AF in the direction of the applied field through the interlayer exchange interaction. Thus, the F and the first layer of the AF together simulate a ferromagnetic interface coupling to the remainder of the AF film. H_{sf} peaks at a certain value of negative interface coupling, then sharply drops with increasing coupling magnitude. This drop is similar to that on the positive coupling side due to this simulated ferromagnetic interface coupling. In fact, the overall shape of the curves appears to be nearly symmetric about the maximum for small values of interface coupling. For very large interface coupling the spin-flop field saturates and is no longer symmetric.

We note that since H_{sf} is not monotonic, there may be some difficulty in obtaining a unique value for the interface coupling. From our calculations, we see that this is a problem only if the coupling is quite strong (greater than 10 T). One possible solution, in this case, is to dope the interface with a nonmagnetic impurity during sample growth. This would likely reduce the magnitude of the effective interface coupling, giving an additional experimental point to compare to the theoretical calculations and thus help obtain a unique value for the interface exchange.

An interesting observation is that H_{sf} appears to be nearly independent of AF thickness near the peak. The position of the peak itself moves in the direction of increasing negative coupling magnitude as the uniaxial anisotropy in the AF is increased. We varied the uniaxial anisotropy over an order of magnitude and determined the peak position in each case; we found a nearly linear dependence.

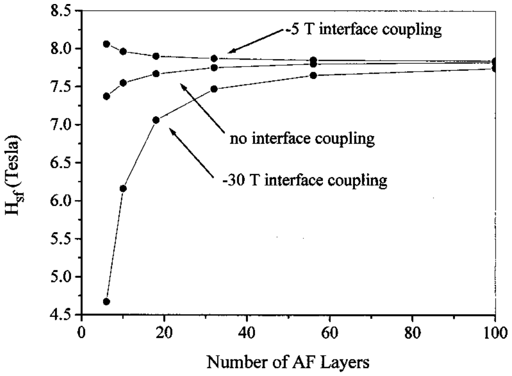

FIG. 4. Dependence of H_{sf} on thickness of the AF film for three interface couplings ($H_{fa}=H_{fb}=-30$, 0, and -5 T). These calculations were for 10 F layers and 15 AF layers.

We also examined the effect of AF thickness on H_{sf}. The results of this study are shown in Fig. 4. For a thick AF film, the spin flop field is nearly independent of thickness. However, for thinner films, surface effects lead to a reduction in the spin-flop field. When the antiferromagnet is coupled to a ferromagnet with a large interfacial coupling, the surface effects can be substantially enhanced and the spin-flop field shows a dramatic change as a function of thickness.

This model suggests a possible experiment for the determination of interface coupling in a given system. One could prepare AF/F and AF only samples with equal AF film thickness and measure the H_{sf} field in each by observing steps in the magnetization verses applied field. Superconducting quantum interference device and vibrating-sample magnetometer systems are easily capable of such measurements and are already commonly used in exchange bias studies. As discussed above, doping the interface with a nonmagnetic impurity during sample growth could produce a range of interface couplings between the ''fully coupled'' AF/F sample and the uncoupled AF only sample. Thus, the trend of H_{sf} verses interface coupling can be better visualized and the interface coupling for the undoped sample can be determined.

In summary, we have investigated the magnetic field required to cause a spin flop in a ferromagnet/antiferromagnet coupled structure. We find that this field depends strongly on the interfacial exchange coupling between the two materials. For reasonable values of coupling, ferromagnetic coupling reduces the spin-flop field and antiferromagnetic coupling increases H_{sf} as compared to field required for an isolated antiferromagnetic film. Thus a measurement of the spin-flop field can determine both the sign and magnitude of the exchange coupling. In contrast to the results for exchange biasing, small deviations from a compensated surface do not substantially influence the results.

This work was supported by ARO Grant No. DAAG55-98-0294 and NSF Grant No. DMR-9970789.

[1] W. H. Meiklejohn and C. P. Bean, Phys. Rev. **105**, 904 (1957).

[2] D. Mauri, H. C. Siegmann, P. S. Bagus, and E. Key, J. Appl. Phys. **62**, 3047 (1987).

[3] A. P. Malozemoff, Phys. Rev. B **35**, 3679 (1987).

[4] N. C. Koon, Phys. Rev. Lett. **78**, 4865 (1997).

[5] T. C. Schulthess and W. H. Butler, Phys. Rev. Lett. **81**, 4516 (1998).

[6] R. E. Camley, B. V. McGrath, R. J. Astalos, R. L. Stamps, and Joo-Von, J. Vac. Sci. Technol. A **17**, 1335 (1999); R. E. Camley and R. J. Astalos, J. Magn. Magn. Mater. **198-199**, 402 (1999).

[7] M. D. Stiles and R. D. McMichael, Phys. Rev. B **59**, 3722 (1999).

[8] K. Takanao, R. H. Kodama, and A. E. Berkowitz (unpublished); K. Takanao, R. H. Kodama, A. E. Berkowitz, W. Cao, and G. Thomas, J. Appl. Phys. **83**, 6888 (1998).

[9] Review article by J. Nogues and I. K. Schuller, J. Magn. Magn. Mater. **192**, 203 (1999).

[10] Joo-Von Kim, R. L. Stamps, B. V. McGrath, and R. E. Camley, Phys. Rev. B **61**, 8888 (2000).

[11] N. J. Gökenmeijer and C. L. Chien (unpublished).

[12] J. Nogues, L. Morellon, C. Leighton, M. R. Ibarra, and I. K. Schuller, Phys. Rev. B **61**, R6455 (2000).

[13] See the review article by R. E. Camley and R. L. Stamps, J. Phys.: Condens. Matter **5**, 3727 (1993).

[14] A. S. Carriço, R. E. Camley, and R. L. Stamps, Phys. Rev. B **50**, 13 453 (1994).

[15] R. E. Camley and Dongqi Li, Phys. Rev. Lett. **84**, 4709 (2000).