Studies of deposition order anomaly of exchange coupling in bilayers and trilayers of NiFe and CoO

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The temperature dependence of the exchange field and coercivity and the effect of deposition order have been studied in a series of bilayer (NiFe/CoO and CoO/NiFe) and trilayer (NiFe/CoO/NiFe) films. A profound difference in the exchange field temperature behavior was observed in samples with NiFe deposited on top of CoO compared to samples with CoO deposited on top of NiFe. When CoO is on top of NiFe, the exchange field follows a linear temperature dependence, while for samples with NiFe on top of CoO, the exchange field has a plateau followed by a rapid decrease. These distinct temperature dependences are reproduced in the NiFe/CoO/NiFe trilayer which contains both geometries. Transmission electron microscopy has been employed to study the interface between the NiFe and CoO layers.
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Exchange coupling between an antiferromagnetic (AF) layer and a ferromagnetic (FM) layer results in a shifted hysteresis loop from zero field, characterized by an exchange field (H_E) accompanied by an increase in the coercivity (H_C). This effect, known as the FM/AF exchange anisotropy, was first discovered in slightly oxidized Co particles that were field cooled to low temperature.[1] The phenomena has subsequently been observed in a number of different FM/AF systems, such as NiFe/FeMn,[2,3] NiFe/NiO,[4] and NiFe/NiCoO,[5] as well as Fe_3O_4/NiO.[6] It is commonly believed that the FM/AF exchange anisotropy is an interfacial effect,[2] although some recent work has questioned its validity.[7] During field cooling through the AF Neel temperature (T_N), magnetic spins near the FM/AF interface are aligned in such a way as to create an unidirectional anisotropy resulting in an effective exchange field acting on the FM layer. This anisotropy breaks the conventional time reversal symmetry commonly found in ferromagnets and reveals itself through a shifted hysteresis loop.

The strength of the exchange coupling has been well studied as a function of the FM layer thickness,[2] magnitude of the field during cooling,[8] processing conditions,[9] as well as its temperature dependence.[3] To date, most theoretical models on AF exchange anisotropy can account for some of the experimental observations, such as the magnitude of H_E and its dependence upon the FM layer thickness.[10,11] But they also predict other features, such as an upper critical thickness of the AF layer,[12] which is not observed experimentally. At relatively high temperatures, the value of H_E appears to have a quasi-linear temperature dependence,[3] which some models have attempted to address.[13] However, as shown in this article, when measurements have been extended to sufficiently low temperature, the temperature dependence of H_E is not linear. Most interestingly, distinctively different temperature dependences exist for samples with layers grown in *different order*. Specifically, samples grown with the FM layer on top of the AF layers are profoundly different from samples with the AF layer grown on top of the FM layer. They exhibit different values of H_E and different temperature dependences. The cause for this deposition order anomaly remains elusive. In this work, we use both bilayer and trilayer samples to study the nature of the anomaly.

For this work, three samples were grown by magnetron sputtering onto Si (100) substrates to study this deposition order anomaly. The geometry of the samples is shown in Fig. 1. CoO was selected as the AF layer while NiFe($Ni_{81}Fe_{19}$) was used as the FM layer. CoO has a Neel temperature (T_N) of 292 K, and was deposited by rf sputtering. NiFe is a soft ferromagnet which was deposited by dc sputtering in a magnetic field of 200 Oe to induce an easy axis of magnetization. The samples were field cooled to 80 K in a 10 kOe field and hysteresis loops were measured as a function of temperatures using a vibrating sample magnetometer (VSM).

To illustrate the deposition order anomaly, we begin by describing the difference in two bilayers [Figs. 1(a) and 1(b)] which differ *only* in the order of layer deposition. The bilayer with NiFe on top of CoO is denoted as sample 1 and the bilayer with CoO on top of NiFe is denoted as sample 2. As shown in Fig. 2, the temperature dependence of H_E for these samples is very different. For sample 2 [Fig. 2(b), CoO on top], H_E follows a linear temperature dependence, while for sample 1 [Fig. 2(a), NiFe on top], H_E has a plateau of constant values at low temperatures followed by a rapid decrease to zero. It is also clear that the value of H_E, at 80 K, for example, is very different for the two cases; the value of H_E for sample 1 is almost twice as large as that of sample 2. Finally, one notes that H_E reduces to zero at the same tem-

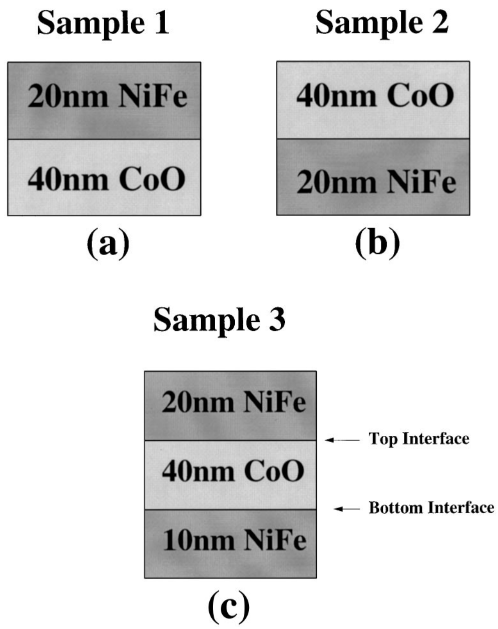

FIG. 1. Bilayer and trilayer structures used in this study. Note sample 1 and sample 2 differ only by the layer order.

perature for both samples. This indicates that the AF layers in the two samples are similar, but the layering order clearly changes both the exchange coupling strength and its temperature behavior.

In the trilayer sample [Fig. 1(c)], there are two interfaces. The top and bottom interfaces correspond, respectively, to the two bilayer samples [Figs. 1(a) and 1(b)]. The thickness of the top FM layer was purposely chosen to be twice as thick as the bottom FM layer. This facilitates the unequivocal determination of H_E for the two FM layers as shown previously.[14] Indeed, distinctively different temperature dependences, similar to those for the two bilayers shown in Fig. 2, have been obtained. These comparisons clearly demonstrate the deposition order anomaly.

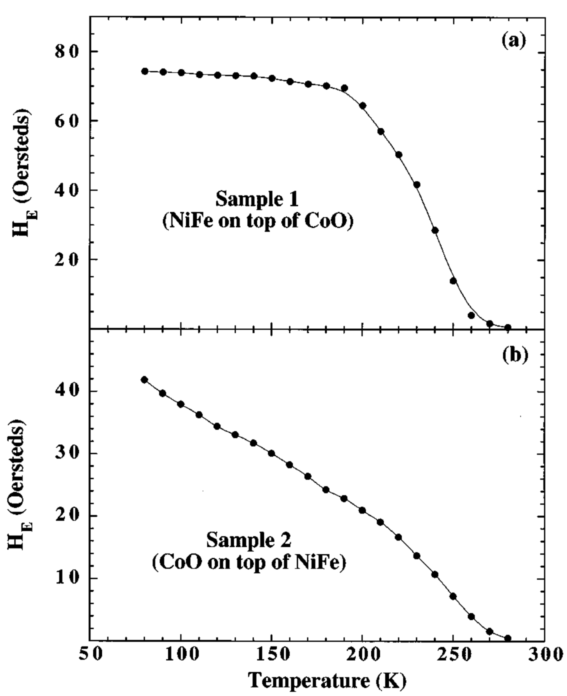

FIG. 2. (a) Temperature dependence of the exchange field for sample 1 with NiFe on top of CoO, (b) temperature dependence of the exchange field for sample 2 with CoO on top of NiFe.

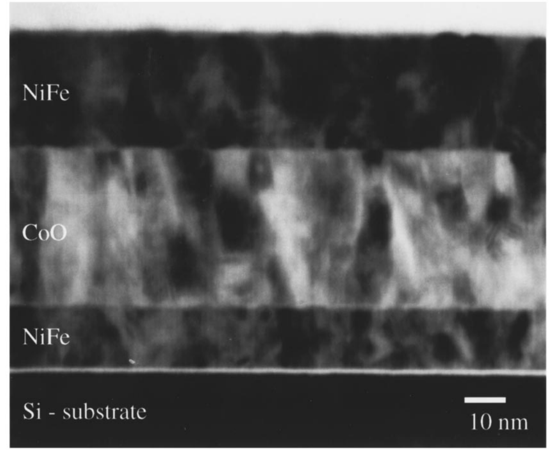

FIG. 3. Cross sectional TEM micrograph of a trilayer sample of 20 nm NiFe/40 nm CoO/10 nm NiFe.

It has been suggested that the roughness of the FM/AF interface may play an important role in determining the strength of the exchange coupling.[10,11] The different temperature dependences of H_E at the two interfaces might be due to roughness of different degree. To investigate this possibility, cross sectional transmission electron microscopy (TEM) has been used to probe the interfaces. In Fig. 3, a cross sectional view of the trilayer is shown. From the TEM micrograph, sharp interfaces can be observed between both the top and bottom interfaces of the CoO layer. The roughness of the interface is less than 1 nm, the same for both interfaces. At higher resolution, lattice images revealed no apparent difference in the top and bottom interfaces. Thus, despite the distinct temperature dependences of H_E, there is no clear structural difference between the two interfaces. It has been shown that the use of an intermediate FM layer doped with a nonmagnetic material between the FM/AF interface can alter the magnitude but not the temperature dependence of H_E.[15]

Finally, we mention the theoretical attempts to account for the apparent linear temperature dependence in H_E at high temperatures. The random field model argues that the magnitude of H_E is proportional to the interfacial domain wall energy at the FM/AF interface, or $H_E \sim (AK)^{1/2}$, where K is the anisotropy constant of the AF layer and A is the AF exchange stiffness parameter.[11] If the AF layer is assumed to have cubic anisotropy, H_E has a linear temperature dependence of $(1-T/T_N)$.[13] By the same token, H_E has a $(1-T/T_N)^{1/2}$ dependence for uniaxial anisotropy.[13] However, regardless of either cubic or uniaxial anisotropy, the temperature dependence does not indicate a saturation in the values of H_E at lower temperatures, contrary to observation. It should also be mentioned that the plateau in H_E is not an isolated feature, and has also been observed in other FM/AF systems, most notably the NiFe/FeMn [see Fig. 4(a) in Ref. 3] and the NiFe/NiMn[16] systems.

In conclusion, we have observed distinct differences in the magnitude and the temperature behavior of H_E for bilayer samples which differ only in the layer order. The exchange field follows either a linear temperature dependence when the AF layer is grown on top of the FM layer or saturates to a fixed value at lower temperatures when the FM layer is grown on top of the AF layer. By using a trilayer sample, we have observed no apparent structural differences at these interfaces using TEM. More experimental work is needed to clarify this anomaly, which has been observed in different AF/FM coupled systems involving both metallic and insulating AF layers.

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