Effects of cooling field strength on exchange anisotropy at permalloy/CoO interfaces

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We have studied exchange anisotropy at ferromagnet/antiferromagnet (FM-AFM) interfaces as a function of cooling field in $Ni_{80}Fe_{20}$ (permalloy) films deposited on bulk single-crystal CoO substrates. Hysteresis loops measured after cooling through the antiferromagnetic ordering temperature in different magnetic fields show that the exchange bias has little dependence on cooling field. Large cooling fields produced hysteresis loops with larger remanent magnetization and larger coercivity. These trends can be explained using a model that assumes that the FM anisotropy axis directions can be influenced by the magnetic history of the AFM. Large cooling fields also led to larger CoO susceptibility, which implies rotation of the CoO spin axes. The simultaneous rotation of the FM anisotropy axes and the AFM spin axes suggests perpendicular coupling at the FM-AFM interface. © *1996 American Institute of Physics.* [S0021-8979(96)17908-8]

Exchange anisotropy, which is magnetic anisotropy caused by the interaction of two neighboring magnetic materials, has been studied in many systems. These include permalloy/FeMn,[1] permalloy/TbCo,[2] and permalloy/$Co_xNi_{1-x}O$.[3] This interest is partly due to the potential for application in the field of magnetoresistive sensors.[4] Recent work has explored the interfacial structure dependence of exchange anisotropy.[5,6] Here we report on a different aspect of the problem, studying how the magnitude of the cooling field affects the interface coupling. The results indicate cooling in large magnetic fields causes the FM anisotropy axes to be oriented parallel to the cooling field and the AFM spin axes to be perpendicular to the cooling field. Taken together, these results suggest a perpendicular coupling between the FM and AFM spins.[7]

The sample preparation is described elsewhere.[5] Briefly, bulk single crystals of CoO with (111) or (100) orientation were given various surface treatments such as sanding, polishing, heating, and ion bombardment. $Ni_{80}Fe_{20}$ (permalloy) films, 100 or 200 Å thick, were deposited at room temperature using a Riber MBE system with a typical pressure of better than 5×10^{-9} Torr during deposition.

The magnetic measurements were performed with a Quantum Design SQUID magnetometer, making use of the magnet reset option to reduce the magnetic field offset in the sample space. The field was applied in the plane of the film. Before each measurement the samples were heated to 400 K, which is above the ordering temperature of CoO (T_N=291 K), but low enough that the heating is unlikely to cause large structural changes.[8] The samples were then cooled to 50 K in a magnetic field, H_{cooling}. Hysteresis loops were then measured over the range (−1500 Oe, 1500 Oe). For each hysteresis loop a large linear background due to the CoO susceptibility χ(AFM) had to be subtracted.

Figure 1 shows two hysteresis loops for a permalloy/CoO sample for two different cooling fields. Both loops exhibit a shift toward the negative field direction. This shift, known as the exchange bias (H_E), is defined as the field halfway between the two field axis intercepts. The coercivity (H_C) is defined as the average magnitude of the two field axis intercepts. The remanence (m_r) represents the average of the two zero field moment values. The reduced remanence (m_r/m_s) is calculated by dividing average zero field moment by the saturation moment, where the saturation moment was determined by averaging over several loops. Understanding the exchange bias magnitude has been the main goal of previous exchange anisotropy studies. However, this report will focus on the other effects visible in Fig. 1, which are that the H_{cooling}=70 kOe loop has larger remanence and larger coercivity.

Figure 2 shows the exchange bias, coercivity, reduced remanence, and CoO susceptibility χ(AFM), for two different samples as a function of the magnitude of the cooling field. We will discuss the FM behavior first and then the AFM behavior. The exchange bias changed very little (<5 Oe) for different cooling fields for all samples measured. For some samples the exchange bias decreased for larger cooling fields while in others it increased or remained constant. The remanence increased with larger cooling fields for seven out of eight samples measured. In most cases, the coercivity also

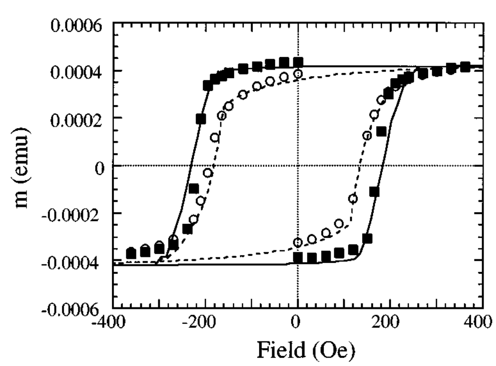

FIG. 1. Magnetization data for a 200 Å permalloy/CoO sample at T=50 K, taken after cooling through two different fields, H_{cooling}=10 kOe (circles) and H_{cooling}=70 kOe (squares). The lines are fits to the model described in the text, where θ_{fan}=10° was used for the solid line and θ_{fan}=35° was used for the dashed line.

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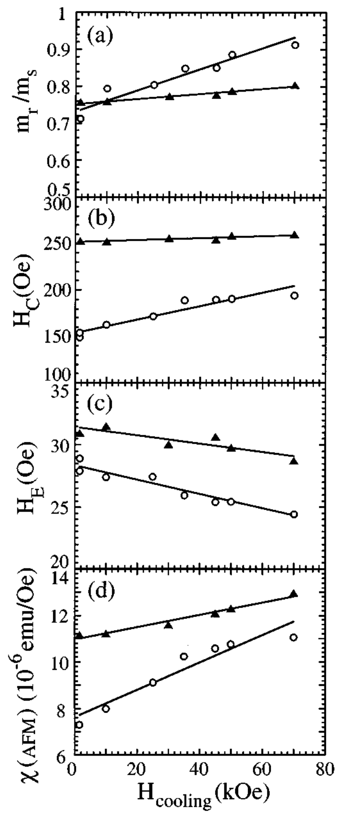

FIG. 2. (a) Reduced remanence (m_r/m_s), (b) coercivity (H_C), (c) exchange bias (H_E), and (d) CoO susceptibility χ(AFM) measured at T=50 K as a function of cooling field magnitude ($H_{cooling}$) for two different samples: (circles) 200 Å permalloy/CoO(111), (triangles) 200 Å permalloy/CoO(100). The lines are guides to the eye.

increased for larger cooling fields, although this data contained some scatter. These results were reversible with cooling field; in other words the values in Fig. 2 did not vary depending on the order of the measurements. The same trends were observed for samples cooled in positive or negative magnetic fields.

The trends toward higher coercivity and remanence are similar to the behavior expected for a ferromagnet having a uniaxial anisotropy axis which changes its direction relative to the applied field. For a single domain FM with uniaxial anisotropy, hysteresis loops will have higher remanence and coercivity if the anisotropy axis is more parallel to the applied field.[9] Therefore the variation in magnetic properties with different cooling fields is possibly due to changes in direction of the anisotropy axes governing the FM behavior.

For this model [Fig. 3(a)], the FM has uniaxial anisotropy but is divided into different regions, each having different directions for the anisotropy axis. The low cooling field state has a wide distribution of anisotropy axes, while for the high cooling field state the anisotropy axes are more parallel to the field direction. To test this model theoretical hysteresis curves were calculated and compared to the data. For the calculation the anisotropy axes were assumed to follow a Gaussian distribution $W(\theta_K)\,\alpha\,\exp[-(\theta_K)^2/2(\theta_{fan})^2]$, where

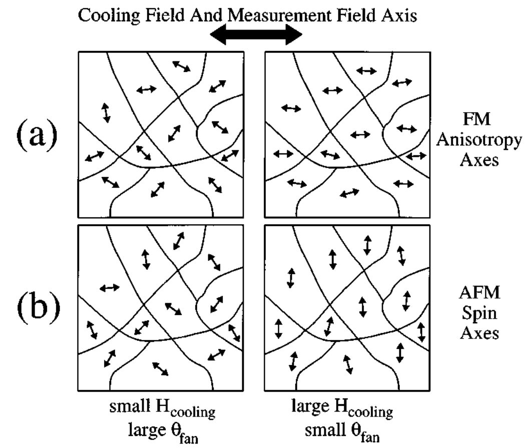

FIG. 3. Illustration of model described in the text, showing a top view of FM regions having various anisotropy axes. Large cooling fields produce FM anisotropy axes which are parallel to the cooling field, and AFM spin axes which are perpendicular to the cooling field.

$W(\theta_K)$ is the weighting function, θ_K is the angle between the anisotropy axis and the field axis, and θ_{fan} is the angular spread of the axes.

Figure 1 shows calculated hysteresis curves with exchange bias, saturation moment, and FM anisotropy set at H_E=24 Oe, m_s=0.00042 emu, and K(FM)=110 000 ergs/cc, respectively to match the data. The only difference between the calculated curves is the angular spread of the axes, θ_{fan}, which changes from 10° to 35°. The agreement with the data implies that the physical properties of the sample are not changing, only the spread in the anisotropy axes.

The most likely source of this change is the magnetic structure in the AFM, which has been changed by heating the sample above the AFM ordering temperature and cooling in a different magnetic field. It is important to note that for these samples the FM coercivity is strongly influenced by interactions with the AFM.[5] The low-temperature coercivity, typically 200 Oe, is much larger than the room temperature coercivity, typically 30 Oe, with a sharp rise near the ordering temperature of the CoO, T_N=291 K. A 200 Å permalloy film deposited under the same conditions onto silicon had coercivities that were smaller (<5 Oe) and did not change with temperature (up to 400 K) or cooling field (up to 7 T). Therefore the mechanism driving the cooling field effects in Figs. 1 and 2 are very likely related to changes in the AFM.

Fortunately the AFM susceptibility data in Fig. 2 provides information about the spin structure in the AFM. Figure 2(d) shows that the low field CoO susceptibility, measured at T=50 K with $|H|$<1.5 kOe, increases for larger cooling fields. This change in the susceptibility indicates that the spin axes of the CoO are more perpendicular to the field if the AFM has been exposed to large magnetic fields. (See Fig. 3) This is because the AFM susceptibility is largest when the spin axis is perpendicular to the applied field. Rotation of AFM spin axes toward directions perpendicular to large magnetic fields has been observed previously in MnO[10] and MnF_2.[11]

To recap, the change in FM remanence and coercivity implies that the FM anisotropy axes are more parallel to the applied field after cooling in large magnetic fields [Fig. 3(a)]. The change in AFM susceptibility implies that the AFM spin axes are more perpendicular to the applied field after cooling in large magnetic fields [Fig. 3(b)]. If one assumes that the FM spins have an energy advantage to align perpendicular to the AFM spins, the FM anisotropy axis rotation can be easily explained. Under this assumption of perpendicular coupling, the large cooling field causes the AFM spin rotation, which then causes the FM anisotropy axis rotation. If perpendicular coupling does exist, it may be related to the perpendicular coupling that has been observed recently between ferromagnetic Fe layers separated by thin Cr layers.[7] Recent work in our laboratory indicates that perpendicular coupling also occurs in the ferromagnet–antiferromagnet system Fe/FeF_2.[12] Other workers have discussed possible perpendicular coupling at permalloy/FeMn interfaces.[13]

In conclusion, we have discovered changes in the behavior of an FM layer adjacent to an AFM, which are due to cooling through T_N in large magnetic fields. The data can be explained by a model where different FM regions have different anisotropy axes, and the distribution of these axes is altered by cooling through different magnetic fields. Susceptibility data from the AFM indicate that the AFM spin axes are also influenced by large cooling fields. Together these two trends suggest that the FM spins and AFM spins may have perpendicular coupling.

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