Long-range exchange coupling between a ferromagnet and an antiferromagnet across a nonmagnetic spacer layer

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The antiferromagnet/ferromagnet exchange coupling giving rise to a shifted hysteresis loop has usually been considered an interfacial effect. We show evidence that this exchange coupling between an antiferromagnet (CoO) and a ferromagnet ($Ni_{81}Fe_{19}$) is long range in nature. Exchange coupling has been observed in tri-layer films consisting of a nonmagnetic noble metal (Ag, Au, and Cu) spacer layer sandwiched between 300 Å CoO and 300 Å NiFe. The strength of the coupling decreases with increasing spacer layer thickness and vanishes at about 55 Å. This suggests that the antiferromagnetic/ferromagnetic exchange coupling is beyond an interfacial effect, and that conduction electrons may be involved in the mediation of the coupling. © *1997 American Institute of Physics.* [S0021-8979(97)60008-0]

There has been continuing interest in exchange coupling ever since the first observation by Meiklejohn and Bean, who found that the hysteresis loop of certain small particles of Co was shifted from the $H=0$ axis.[1,2] This offset was attributed to an exchange coupling between antiferromagnetic cobaltous oxide shell surrounding the ferromagnetic Co particle. Subsequently, exchange coupling has been realized in ferromagnet (FM)/antiferromagnet (AF) bilayers, such as $Ni_{81}Fe_{19}$/FeMn, $Ni_{81}Fe_{19}$/CoO, $Ni_{81}Fe_{19}$/NiO, and $Ni_{81}Fe_{19}$/NiCoO,[3–6] where the exchange coupling can be more systematically explored. In these bilayers, after the sample has been field-cooled through the Néel temperature of the AF material, the hysteresis loop of the FM material is shifted due to the exchange coupling. Recently, the FM/AF exchange coupling has also been utilized to construct spin-valve field-sensing devices, in which exchange coupling is employed to shift the hysteresis loop of the FM material in a prescribed manner.[7]

Despite these advances, many aspects of the FM/AF exchange coupling remain poorly understood. The value of the exchange anisotropy field H_E has been found to depend on the thicknesses of the FM[3] and the AF layers,[8] temperature,[9] and even the order of the layers;[10] that is, the behavior of AF/FM and FM/AF are distinctively different. The exact arrangement of the spins of the FM and AF layers is still highly controversial as well. Central to the understanding of the FM/AF coupling is whether or not, it is an interfacial effect. Experimentally, the value of the exchange bias field H_E in the exchange coupled systems has a $1/t_{\mathrm{FM}}$ dependence, where t_{FM} is the thickness of the ferromagnetic layer.[3] This fact has been cited as convincing evidence that exchange coupling is an interfacial effect, which practically all theoretical models have assumed.[11,12] In this work, we have probed this assertion by purposely separating the FM and the AF layers with a nonmagnetic spacer layer. This observation of exchange anisotropy *across* a nonmagnetic spacer layer demonstrates that the exchange coupling is more complex than a simple interfacial effect.

We have chosen the layer structure of FM/spacer/AF for this study. Permalloy ($Ni_{81}Fe_{19}$) was used as the FM material because of its soft magnetic properties. Our sputtered permalloy thin films show a small coercivity of about 2 Oe and a squareness greater than 97%. CoO was chosen as the AF material because of its convenient Néel temperature of $T_N=292$ K, and the fact that exchange coupling has been well established in $Ni_{81}Fe_{19}$/CoO bilayers.[14] For the spacer layers, the noble metals Cu, Ag, and Au were chosen.

The samples were fabricated in a magnetron sputtering system with programmable shutter operation and substrate positioning. The base pressure was about 8×10^{-8} Torr, and sputtering was conducted at a pressure of 6 mTorr of Ar. Structures with a wedged spacer layer were produced so that all samples had identical deposition conditions and that the spacer layer thickness was the only variable. The layer structure for this work consists of 100 Å Cu/300 Å $Ni_{81}Fe_{19}$/wedged spacer/300 Å CoO/100 Å Cu. Copper was used to provide a clean underlayer for the subsequent structure, and also as a capping layer for protective purposes. The 300 Å of $Ni_{81}Fe_{19}$ was deposited in a magnetic field by positioning a permanent magnet inside the sputtering chamber. This magnetic field provided the permalloy with a uniaxial anisotropy with its easy axis perpendicular to the wedge direction of the spacer layer. The growth rate of each deposition was calibrated by the use of crystal oscillators, small-angle x-ray diffraction, and profilometry. Although the magnetic characteristics among samples from separate productions show some variations, the samples from the same wedge exhibit excellent self-consistency. Clearly, this is the advantage of using samples with a wedged constituent layer.

High angle x-ray diffraction showed that, in all cases, the permalloy layer, the CoO layer, and the noble metal (Cu, Ag, or Au) layer are all (111) oriented. Films with a constant spacer layer thickness were also produced, and data from these films agreed with those from the wedge films. Transmission electron microscopy (TEM) was used to evaluate the structure of the trilayer, and the results for Au spacer layer

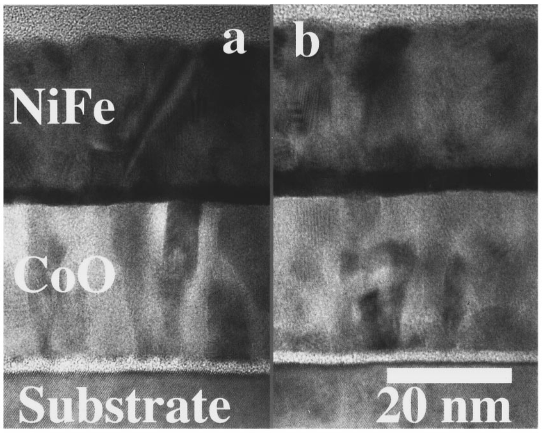

FIG. 1. TEM picture of Au spacer (a) with a 25 Å spacer layer, exhibits exchange coupling, (b) with a 45 Å spacer layer, exhibits no exchange coupling.

are shown in Fig. 1. There are no discernible differences among samples with various Au layer thickness, nor apparent pinholes or discontinuous spacer layers.

Magnetic hysteresis loops measurements were made on a Digital Measurement Systems vibrating sample magnetometer (VSM). Before each measurement, each sample was first field-cooled in a field of 10 kOe to 80 K with the magnetic field parallel to the easy axis of the permalloy. Representative hysteresis loops at 80 K for samples with a Au spacer layer are shown in Fig. 2. The hysteresis loops are all shifted from $H=0$, a telltale sign of exchange coupling. The exchange field H_E is defined as the displacement of the loop from $H=0$. The data in Fig. 2 show that the value of H_E decreases for increasing Au layer thickness t_{Au}. There is still a small but measurable value of H_E for the sample with $t_{\mathrm{Au}}=32$ Å. Samples that exhibit exchange coupling also exhibit a much increased coercivity (H_c). The value of H_c is defined as one half of the loop width at $M=0$. As shown in Fig. 2, the value of H_c also decreases with increasing t_{Au}. Only when $t_{\mathrm{Au}}\geqslant 36$ Å, $H_E=0$, and $H_c\approx 2$ Oe, all the characteristics of permalloy with no exchange coupling. These measurements are repeatable, except sometimes a small decrease in the exchange field of 2% to 4% is observed. This is sometimes referred to as the ''training'' effect,[13] which is minimal in the present case. It should be emphasized that the shift of the hysteresis loop, with clear-cut exchange coupling, has been observed in systems in which the AF and FM layers are *separated* by a Au layer of various thickness. Similar results have been observed when the spacer layer is either Cu or Ag.

The temperature dependence of H_E and H_c of 300 Å $Ni_{81}Fe_{19}$/Cu/300 Å CoO for $t_{\mathrm{Cu}}=4.7$ and 17.3 Å are shown in Fig. 3. The exchange field H_E is nearly constant at low temperatures but decreases rapidly as the Néel temperature T_N of CoO is approached, and vanishes above T_N. The coercivity H_c, having a different temperature dependence, decreases steadily with increasing temperature over the entire temperature range, and retains the value of about 2 Oe at $T\geqslant T_N$, the value for uncoupled $Ni_{81}Fe_{19}$. For samples with different t_{Cu} the temperature dependence is similar although the values of H_E and H_c are different.

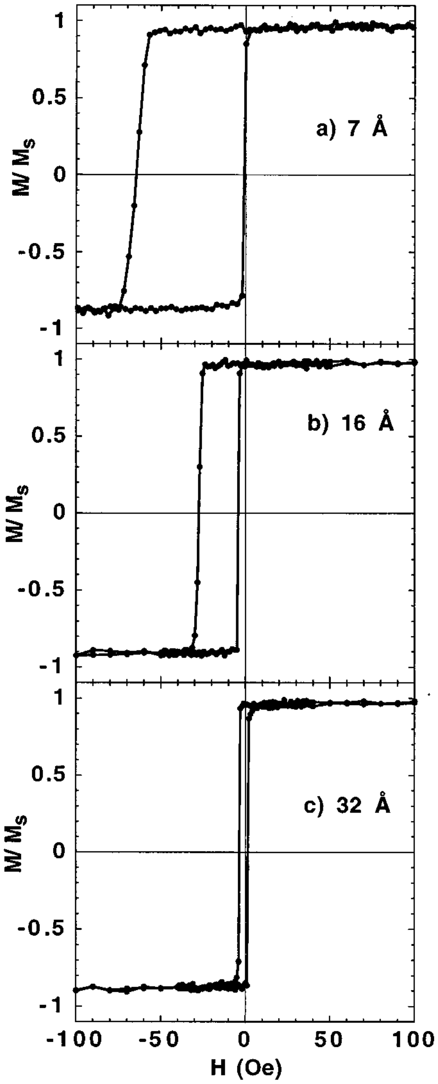

FIG. 2. Hysteresis loops at 80 K for $Ni_{81}Fe_{19}$(300 Å)/Au(x)/CoO(300 Å): (a) $x=7$ Å, (b) $x=16$ Å, and (c) $x=32$ Å.

In Fig. 4, the values of H_E at 80 K of various samples of 300 Å $Ni_{81}Fe_{19}$/spacer/300 Å CoO are shown as a function of the spacer layer thickness. Excluded are the data for extremely small spacer layer thickness ($\leqslant 3$ Å), where the values of H_E vary widely. However, the results for spacer thickness larger than 3 Å are very consistent. In all cases, the value of H_E decreases with the spacer layer thickness, and becomes zero above a critical thickness t_c. Experimentally, among the noble metal spacer materials, the critical thickness t_c is 56±4 Å for Ag, 36±4 Å for Au, and 30±4 Å for Cu.

These results rather conclusively demonstrate exchange coupling between a FM layer and an AF layer *across* a nonmagnetic spacer layer. One might suspect that pinholes through the spacer layer allow for the observed, but unexpected exchange coupling across the spacer layer. Pinholes or discontinuous layers most likely exist in extremely thin spacer layers, illustrated by our erratic results when the

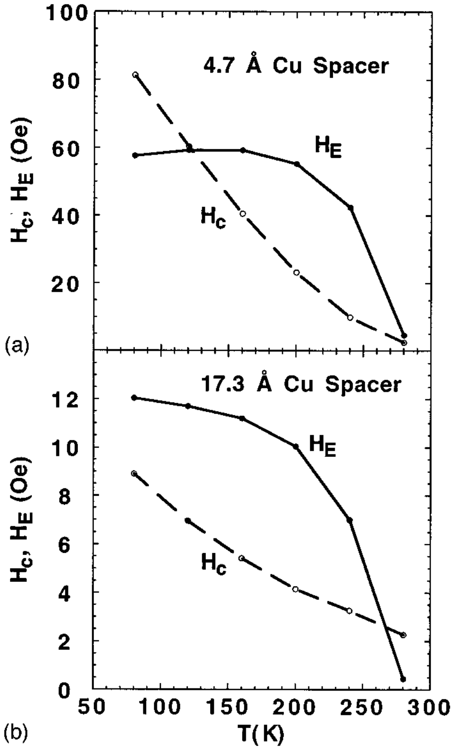

FIG. 3. Temperature dependence of exchange field H_E (solid line) and coercivity H_c (dashed line) of $Ni_{81}Fe_{19}$(300 Å)/Cu(x)/CoO(300 Å): (a) $x=4.7$ Å and (b) $x=17.3$ Å.

spacer layer is less than 3 Å. However, the TEM results shown in Fig. 1 do not reveal pinholes of disrupted spacer layers when the spacer layers are in the nm range. The quality of the layer structure is similar for small and large spacer layer thickness where exchange coupling is present and absent, respectively. It should also be pointed out that antiferromagnetic interlayer coupling has been observed in many Co/Cu and Fe/Cu[14,15] multilayers, where the spacer layers is only about 10 Å. The spacer layer in these systems must not be pinhole-prone in the nm range or the antiferromagnetic interlayer coupling would be excluded by direct coupling. Finally, if the observed exchange coupling is due to pinholes, it is difficult to comprehend that the dependence of H_E on the spacer layer thickness, as shown in Fig. 4, would be so regular. The evidence is therefore compelling to conclude that long-range exchange coupling exists across a spacer layer up to a distance of about 55 Å. This indirect coupling is likely to be mediated by the conduction electrons in the spacer layer, although the mechanism remains yet to be determined.

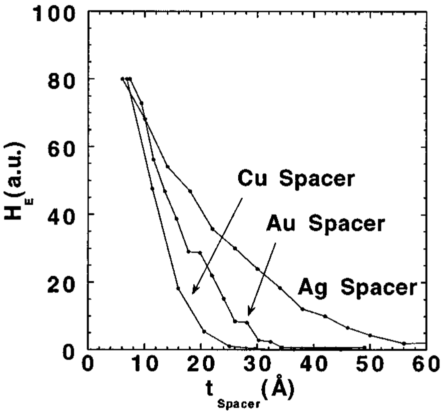

FIG. 4. Exchange field H_E vs spacer layer thickness for $Ni_{81}Fe_{19}$(300 Å)/spacer(x)/CoO(300 Å) with a Cu, Au, and Ag spacer layer.

In conclusion, we have shown evidence that exchange coupling is present in trilayers of $Ni_{81}Fe_{19}$/(Cu, Ag, Au)/CoO for a spacer thickness less than the critical thickness t_c. The value of t_c is found to be 56±4 Å, 36±4 Å, and 30±4 Å for Ag, Au, and Cu, respectively. The large values of t_c indicate that the FM/AF exchange coupling is long range and not merely an interfacial effect.

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