# Spiraling Spin Structure in an Exchange-Coupled Antiferromagnetic Layer

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Using trilayers of permalloy/FeMn/Co with various thicknesses $t_{\mathrm{AF}}$ of the antiferromagnetic FeMn, we have observed evidence of a spiraling spin structure within FeMn. For $t_{\mathrm{AF}} < 90$ Å, the turn angle $\theta$ of the spiral varies as $\theta = (1.76°/\text{Å})t_{\mathrm{AF}}$.

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The exchange coupling between a ferromagnet (FM) and an antiferromagnet (AF) has been intensively studied in recent years because of the intriguing physics and its center role in spin-valve devices [1–4]. The hysteresis loop $M(H)$ of an isolated FM is always centered at the origin and with the symmetry of $M(H) = -M(-H)$, where $M$ is the magnetization and $H$ the external field. The detailed characteristics (e.g., domain patterns and walls) of switching from $-M$ and $+M$ is the same as those from $+M$ to $-M$. In a FM/AF bilayer, a unidirectional exchange anisotropy can be established, most often by cooling the bilayer in an external magnetic field from higher temperatures. The magnetization direction of the FM layer during field cooling determines the anisotropy axis of the AF layer and the unidirectional exchange coupling. The hysteresis loop of the FM is now shifted away from $H = 0$ by the amount of the exchange bias field $H_E$, accompanied by an enhanced coercivity $H_c$. Much attention has been devoted to the studies of this scientifically interesting and technologically important intriguing phenomenon.

It is generally recognized that the spin structure of the AF holds the key to the understanding of this intriguing phenomenon. Simple theoretical models have been proposed, wherein the AF structure has been assumed to be static, i.e., the AF spin structure remains rigid throughout the magnetization reversal process of the FM layer [1]. In such models, the exchange bias is purely an interfacial phenomenon. The exchange interaction between the FM moments and the interfacial AF moments gives rise to an effective static magnetic field $H_E$, which shifts the hysteresis loop of the FM layer, in apparent agreement with the experimental results.

However, these simple models are incompatible with a number of experimental results, least of which, the enormous values of $H_E$ predicted. Recently, measurements of the motion of a single domain wall in a FM/AF bilayer with a wedged FM layer show an acute asymmetry between the magnetization reversal from $+M$ to $-M$ and that from $-M$ to $+M$ [5,6]. Models with static AF spin structures expect no such asymmetry since the interfacial interactions introduce only a static field. These experiments demonstrate that the AF spin structure in a FM/AF bilayer is not static. Other contrasting results include the strong thickness dependence of exchange bias on AF layers with large thicknesses and the memory effect of the field-cooling history [7,8].

More realistic theoretical investigations have concluded a dynamic AF spin structure. Because of the strong interactions at the FM/AF interface, the interfacial AF spins are locked in with the FM magnetization. Mauri *et al.,* Koon, Schulthess *et al.,* and Stiles *et al.* have shown that when the magnetization of the FM layer is reversed, a spiraling spin structure is formed in the AF layer with an AF domain wall extending into the interior of the AF [9–12]. However, there has been no experimental evidence of the spiraling AF spin structure or the AF domain width.

In this work, using FM1/AF/FM2 trilayers, we have observed that the two FM layers of FM1 and FM2 are coupled across a thin intervening AF layer. More importantly, the angle $\theta$ between the magnetization axes of FM1 and FM2 across the AF layer with a thickness $t_{\mathrm{AF}} < 90$ Å has been found to depend *linearly* on the AF layer thickness $t_{\mathrm{AF}}$ as $\theta = gt_{\mathrm{AF}}$, where $g = 1.76°/\text{Å}$. This is the first experimental evidence of a spiraling spin structure within the AF layer in an exchange-coupled system. Previously, a roughness driven 90° coupling in $\mathrm{Fe_3O_4/NiO/Fe_3O_4}$ trilayers that does not depend on the thickness of NiO has been reported [13].

Trilayers of Py(200 Å)/FeMn($t_{\mathrm{AF}}$)/Co(100 Å) have been grown in a sputtering system with a base pressure of $6 \times 10^{-8}$ torr. The trilayers were grown on a Cu(100 Å) underlayer to promote (111) texture and capped with a Cu(100 Å) to prevent oxidation. Two different FMs of Co and Py = $\mathrm{Ni_{81}Fe_{19}}$ were used to exploit the large difference in the magnetic anisotropy. To eliminate run-to-run variations, all the samples of $t_{\mathrm{AF}} \leq 100$ Å that provide the essential results were taken from a single specimen of Py(200 Å)/FeMn($t_{\mathrm{AF}}$)/Co(100 Å) containing a wedged FeMn layer. Many small samples were then cut along the FeMn wedge direction, each with a specific value of $t_{\mathrm{AF}}$ and individually measured by a vibrating sample magnetometer.

An example of the hysteresis loop of Py(200 Å)/FeMn($t_{\mathrm{AF}}$)/Co(100 Å) with $t_{\mathrm{AF}} = 150$ Å at 400 K, before setting the exchange bias, is shown in Fig. 1a. Because of the large difference in their intrinsic magnetic anisotropy, the Py layer shows a narrow loop while the Co layer shows a wide loop. Consequently, there exists

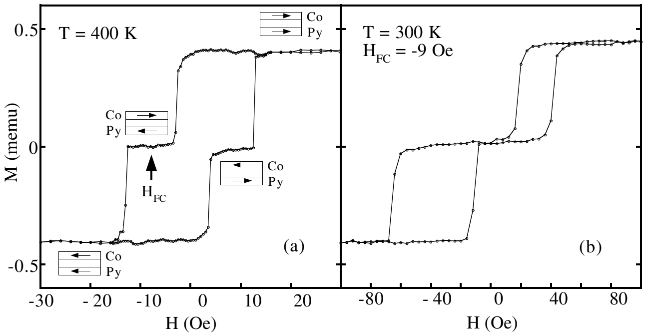

FIG. 1. Hysteresis loops of Py(200 Å)/FeMn($t_{\mathrm{AF}}$)/Co(100 Å) for $t_{\mathrm{AF}} = 150$ Å (a) at 400 K without exchange bias. The arrow indicates the plateau field $H_{\mathrm{FC}}$ at which the magnetization of Co and Py are opposite. (b) At 300 K after field cooling at $H_{\mathrm{FC}} = -9$ Oe. The Co and Py loops are shifted to the left and right, respectively.

a plateau at which the magnetizations of Co and Py are opposite, as indicated by the arrow in Fig. 1a. We have taken advantage of this fact by field cooling the sample from 400 to 300 K at the plateau field of $H_{\mathrm{FC}} = -9$ Oe, at which the Co and Py layers were field cooled with their magnetizations in opposite directions. After field cooling, the spin structure of the intervening AF layer will be strongly coupled to, and bounded by, two FMs with opposite magnetizations. Another important benefit of this unusual field-cooling procedure is that the Py and Co layers acquire exchange bias with opposite anisotropy axis as shown in Fig. 1b. One can unequivocally identify the Co loop shifted to the left with a large $H_c$ and the Py loop shifted to the right with a small $H_c$. If the trilayer were field cooled in a large magnetic field, as it is usually done, one would have obtained two overlapping Co and Py loops, which could not be separately analyzed with ease.

The angular dependence of an exchange-coupled FM has been previously determined [14]. The exchange field $H_E$ and coercivity $H_c$ have the angular dependence of $\cos\phi$ (unidirectional) and $\cos 2n\phi$ (uniaxial), respectively, where $n$ is an integer and $\phi$ is the angle between the anisotropy axis and the applied field $H$ during the hysteresis loop measurements. Consequently, one obtains the largest values of $H_E$ and $H_c$ at $\phi = 0$ and $\phi = \pi$, at which a square loop is obtained as shown in Fig. 1b. Conversely, one can also determine the unidirectional anisotropy axis by measuring angular dependence of either $H_E$ or $H_c$ and note the angle at which $H_E$ and $H_c$ are maximal.

Using the technique of field cooling at the plateau field, we have studied Py(200 Å)/FeMn($t_{\mathrm{AF}}$)/Co(100 Å) trilayers with various $t_{\mathrm{AF}}$ as shown in Fig. 2. For a large $t_{\mathrm{AF}}$ (e.g., 300 and 150 Å, shown in Figs. 2a and 2b), the axes of the Co and Py magnetizations are found to be opposite to each other and both loops are square. However, at $t_{\mathrm{AF}} < 90$ Å, while the Co loop remains square, the Py loop has become slanted, as shown in Figs. 2d–2f, indicating that the anisotropy axis of the Py layer has changed from being opposite to that of Co. As shown in Fig. 2, regardless of the value of $t_{\mathrm{AF}}$, the unidirectional anisotropy of the Co layer is always along the same direction (opposite to the cooling field direction) due to its larger intrinsic magnetic anisotropy.

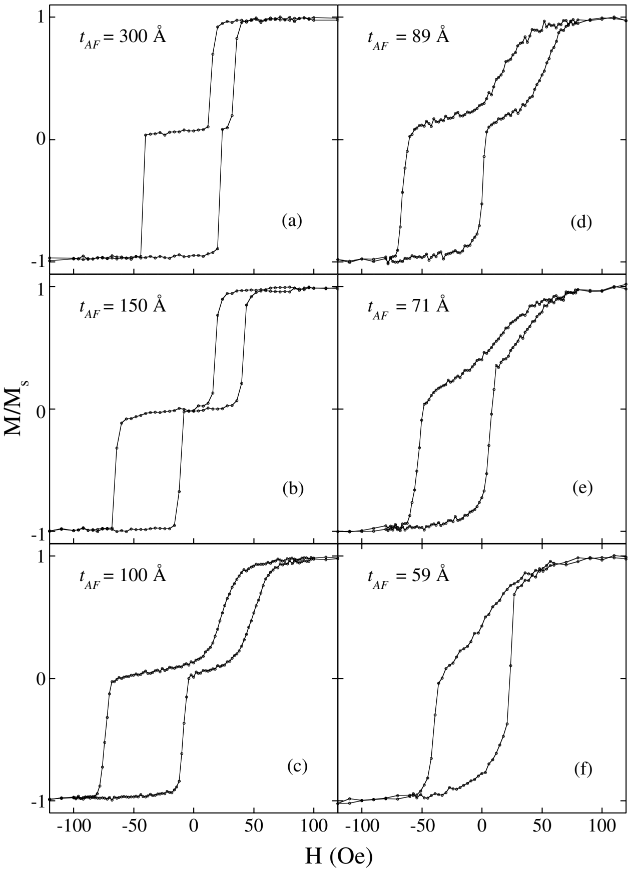

FIG. 2. Hysteresis loops of Py(200 Å)/FeMn($t_{\mathrm{AF}}$)/Co(100 Å) with $t_{\mathrm{AF}}$ of (a) 300 Å, (b) 150 Å, (c) 100 Å, (d) 89 Å, (e) 71 Å, and (f) 59 Å at 300 K after field cooling at $H_{\mathrm{FC}}$ from 400 K.

For these samples with $t_{\mathrm{AF}} < 90$ Å, we have determined the turn angle $\theta$ between the magnetization axes of Co and Py by measuring a series of hysteresis loops with the magnetic field applied at various angles $\beta$ with respect to the cooling field direction. Representative results of the sample with $t_{\mathrm{AF}} = 71$ Å are shown in Fig. 3. The result shown in Fig. 3a with $\beta = 0$ is the same as that in Fig. 2e, where the Co loop shows maximum $H_c$. As $\beta$ is varied, the Py loops show a larger $H_c$, whereas the Co loops show a smaller $H_c$. At $\beta = \beta_a = 55°$, the Py loop acquires the largest $H_c$, thus indicating the direction of its unidirectional anisotropy axis is at an angle $\theta = \pi - \beta_a = 125°$ from that of the Co layer. In this manner, we have determined the value of $\theta$ for all the samples with $t_{\mathrm{AF}} < 90$ Å. The Py loops with $t_{\mathrm{AF}} = 89$ Å and 100 Å in Fig. 2 appear slightly slanted. But the largest $H_c$ has been found near $\beta_a = 0° \pm 10°$, hence $\theta \approx 180°$.

The measured turn angle $\theta$ between Co and Py for all the samples of Py(200 Å)/FeMn($t_{\mathrm{AF}}$)/Co(100 Å) are shown

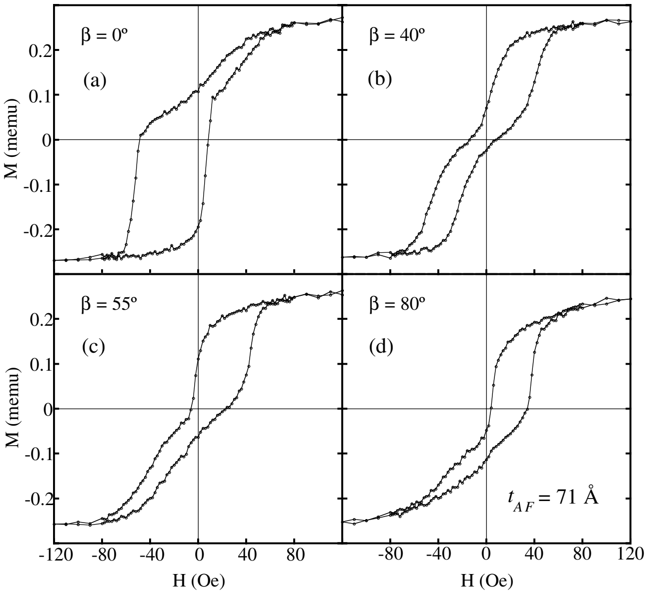

FIG. 3. Hysteresis loops of Py(200 Å)/FeMn($t_{\mathrm{AF}}$)/Co(100 Å) trilayers at 300 K after field cooled at $H_{\mathrm{FC}}$ with $\beta$ of (a) 0°, (b) 40°, (c) 55°, and (d) 80°, where $\beta$ is the angle between the magnetic field $\mathbf{H}$ and the field cooling direction.

in Fig. 4c. For $t_{\mathrm{AF}} > 90$ Å, the magnetization axes of the Py and the Co layers are opposite due to the special field cooling procedure, whereas, for $t_{\mathrm{AF}} < 90$ Å, $\theta$ is less than $\pi$. Most importantly, for $t_{\mathrm{AF}} < 90$ Å, $\theta$ has been found to vary linearly with $t_{\mathrm{AF}}$ as $\theta = g_o t_{\mathrm{AF}}$, where $g_o = 1.76°/\text{Å}$, as shown in the inset of Fig. 4c. Because the AF spin structure is strongly coupled with Co at one end, and with Py at the other end, the turn angle $\theta = g_o t_{\mathrm{AF}}$ between Co and Py layers reveals a spiraling AF spin structure within the AF layer. The atomic spacing of fcc FeMn along the (111) direction is 2.09 Å, from $g_o = 1.76°/\text{Å}$, the pitch angle between adjacent AF planes is $(\Delta\theta)_0 = 3.68°$. For AF layers with $t_{\mathrm{AF}} < 90$ Å, because the pitch angle of the spiral remains the same at $(\Delta\theta)_0 = 3.68°$, the length of the spiral is dictated by $t_{\mathrm{AF}}$, and consequently, the turn angle $\theta$ of the spiral must be less than $\pi$ and varies as $g_o t_{\mathrm{AF}}$. We have not been able to determine the behavior for $t_{\mathrm{AF}} < 53$ Å because for these samples, the plateau at which we perform the special field cooling can no longer be located.

The length of the spiraling AF spin structure is the thickness of the AF domain wall predicted theoretically. In general, the domain wall thickness can be long in the case of a spiral with very small pitch angle. However, there is a minimum AF domain wall thickness, which is known theoretically to be proportional to $(A_{\mathrm{AF}}/K_{\mathrm{AF}})^{1/2}$, where $A_{\mathrm{AF}}$ and $K_{\mathrm{AF}}$ are the stiffness and anisotropy constants of the AF [9–12]. In the present case, the value of 90 Å is the smallest AF domain wall thickness with the largest pitch angle $(\Delta\theta)_0$. Since the AF wall thickness depends on temperature and material, the value of 90 Å is relevant only for FeMn at 300 K, at which our measurements have been made.

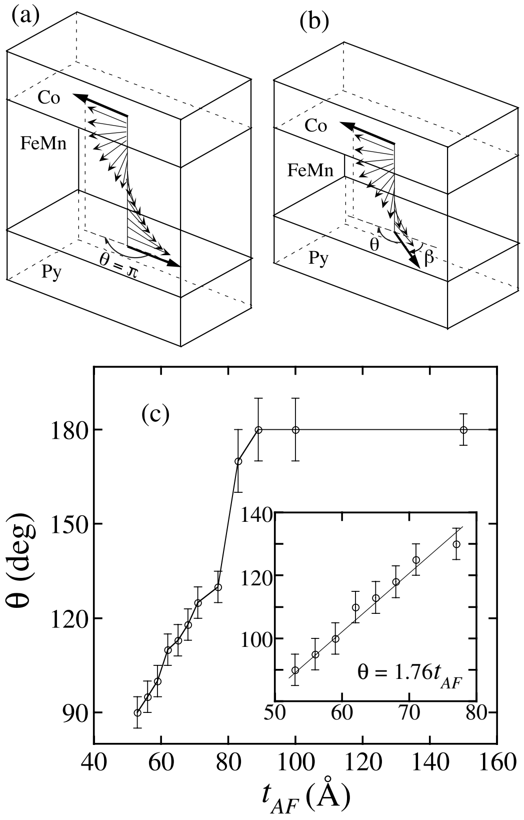

FIG. 4. Schematic diagram of the spin structures in Py/FeMn/Co trilayers (a) for FeMn thickness $t_{\mathrm{AF}} > 90$ Å with $\theta = \pi$ between the magnetizations of Co and Py, and (b) for $t_{\mathrm{AF}} < 90$ Å and $\theta < \pi$. For clarity, only one AF sublattice of FeMn is depicted. (c) Thickness dependence of $\theta$ on $t_{\mathrm{AF}}$. The inset shows the linear relation of $\theta = 1.76 t_{\mathrm{AF}}$.

The special field-cooling procedure at the plateau field that we have used, in which the magnetization axes of Co and Py are opposite, is essential for the observation of the spiraling AF spin structure. The emerging picture is as follows. For AF with large thicknesses ($t_{\mathrm{AF}} > 90$ Å), a spiraling AF spin structure is formed between the Co and the Py layers with a turn angle of $\theta = \pi$, as schematically shown in Fig. 4a, in which only one AF sublattice is depicted for clarity. The pitch angle $\Delta\theta$, which is dictated by $t_{\mathrm{AF}}$ in each case, is less than the value of $(\Delta\theta)_0 = 3.68°$. Thus, a spiraling AF spin structure can exist in thick AF layers as well. This accounts for the fact that exchange bias has been found to systematically depend on AF layers several hundred Å thick [7].

As the AF thickness $t_{\mathrm{AF}}$ is reduced, the pitch angle $\Delta\theta$ will correspondingly be increased, until at $t_{\mathrm{AF}} = 90$ Å, the maximum pitch angle $\Delta\theta_0$ is reached. As $t_{\mathrm{AF}}$ is decreased to below 90 Å, with the pitch angle fixed at $\Delta\theta_0$, the spiral can only be shortened, resulting in a turn angle less than $\pi$, as depicted in Fig. 4b. The shortened spiral compels the rotation of the magnetization axis of the Py layer, which has a weaker intrinsic anisotropy. Hence, the direction of the unidirectional anisotropy of the Py layer will be dictated by the length of the spiral and thus depends linearly on $t_{\mathrm{AF}}$. Because of the strong anisotropy of the Co layer, its unidirectional anisotropy axis is always along the field-cooling axis. It may be mentioned that the spiraling spin structures in Figs. 4a and 4b are intended to illustrate the salient features by exaggerating the pitch angle, even though the maximum pitch angle is only 3.68°.

In the present Py/FeMn/Co trilayers, the Co layer anchors the AF spin structure, while the spiraling AF spin structure is revealed by the rotation of the Py layer. The situation is relevant to that of an exchange-biased Py/FeMn bilayer, in which a spiraling AF spin structure upon magnetization reversal has been predicted [9–12]. The spiraling AF spin structure also accounts for the dependence of exchange bias on $t_{\mathrm{AF}}$ [7].

In summary, we have observed evidence of a spiraling AF spin structure in Py/FeMn/Co trilayers using a special field-cooling procedure. Such a spiraling AF spin structure has been previously indicated by theoretical models but not observed experimentally. For FeMn at 300 K, the minimum AF domain wall, represented by the shortest full spiral, has been found to be 90 Å.

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