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Dependence of exchange coupling in permalloy/$Cr_{82}Al_{18}$ bilayers on the constituent layer thickness

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Due to a weaker exchange coupling, the coercivity in permalloy/$Cr_{82}Al_{18}$ bilayers of thicknesses t_{FM} and t_{AF}, respectively, has been found to vary as $1/t_{FM}^{3/2}$ at room temperature, a behavior previously only observed at low temperatures. At room temperature, the exchange field decreases when t_{AF} is less than 40 nm and vanishes at 25 nm. Switching in wedged-permalloy/$Cr_{82}Al_{18}$ bilayers consists of two macroscopic domains with one domain wall moving along the wedge direction. © *2000 American Institute of Physics.* [S0021-8979(00)69108-9]

A great deal of attention has recently been focused on the ferromagnetic (FM)/antiferromagnetic (AF) exchange coupling because of the intriguing phenomena[1] and applications in spin-valve giant magnetoresistance devices for sensing magnetic fields.[2] In exchange-coupled FM/AF bilayers, the hysteresis loop is shifted from the origin by an amount known as the exchange field H_E, accompanied by an enhanced coercivity H_C. The characteristics of the FM/AF exchange coupling depend strongly on the microstructure and the thickness of the constituent materials.[3–10] The original simple model with a static AF spin structure does not account for the observed characteristics.[1] The importance of the AF domain wall with energy $4(A_{AF}K_{AF})^{1/2}$, where A_{AF} and K_{AF} are, respectively, the exchange stiffness and the anisotropy constant of the AF layer,[4] has been indicated by a number of recent micromagnetic calculations.[11–13]

Because exchange bias is a result of interactions across the interface between the FM and the AF layers, H_E is inversely proportional to t_{FM}, as experimentally observed.[3,4] The exchange field generally decreases as temperature approaches the so-called blocking temperature T_B.[5] While a nonzero H_E is usually considered as a signature of exchange bias, it has recently been demonstrated that the value and even the sign of H_E can be drastically altered by the field-cooling process.[14] On the other hand, the value of the enhanced H_C, also a telltale sign of exchange coupling, is uniquely defined at each temperature, regardless of the value of H_E.

The coercivity is known to depend on the quality of the FM/AF interface, across which the exchange coupling is transmitted. In Py/CoO and Py/FeMn bilayers (permalloy $=Ni_{81}Fe_{19}$), the coercivity has been found to vary as $1/t_{FM}$ (where t_{FM} is the FM layer thickness) at high temperatures,[3] but shows a $1/t_{FM}^{3/2}$ dependence at low temperatures.[15] The observed $1/t_{FM}^{3/2}$ behavior of H_C is consistent with the theoretical predictions based on the random-field interactions at the FM/AF interface. In addition to the dependence on t_{FM}, the exchange coupling has also been found to depend on the AF layer thickness t_{AF}. For small values of t_{AF} (e.g., less than 10 nm), the variation of the exchange coupling is due to a reduction of the Néel temperature T_N, resulting from the finite-size effects.[16] However, for relatively large values of t_{AF}, the observed dependence is probably a manifestation of the domain structure in the AF layers.[17]

To reveal the nature of the exchange coupling in FM/AF bilayers, it is essential to study the dependence not only of H_E but also of H_C on the thickness of both the FM and the AF layers. Such studies can be conveniently made using wedged constituent layers. Another distinct advantage of using a wedged FM layer is the realization of a simple domain structure during switching. We have recently shown that, by taking advantage of the $1/t_{FM}$ dependence of H_E and H_C, switching in wedged FM/uniform AF bilayers involves only two macroscopic domains separated by one domain wall.[18]

In this work we study the dependence of H_E and H_C on the thickness of both the FM and the AF layers by using FM/AF bilayers with either a wedged FM layer of permalloy or a wedged AF layer of $Cr_{82}Al_{18}$. For high Cr contents, the $Cr_{100-x}Al_x$ alloys are antiferromagnetic with relatively high values of T_N. The magnetic measurements using vibrating sample magnetometry (VSM) and magneto-optical Kerr effect (MOKE) have been performed at room temperature. While we have observed H_E to vary as $1/t_{FM}$, more unusually, H_C has been found to vary as $1/t_{FM}^{3/2}$ at room temperature, a behavior previously only observed at low temperatures. We have found the onset of the exchange coupling of Py/$Cr_{82}Al_{18}$ bilayers at room temperature for AF layers with thicknesses larger than a critical value. We have also observed the macroscopic domain features in Py/CrAl, qualitatively similar to that in Py/FeMn, although the switching behaviors of Py/CrAl are noticeably different.

The specimens of Py(8 nm)/$Cr_{82}Al_{18}$(t_{AF}) and Py(t_{FM})/$Cr_{82}Al_{18}$(53 nm), one with a wedged CrAl layer and the other with a wedged Py layer, were deposited onto Si substrates in a computer-controlled multisource deposition system using an alloyed target of Py and an Al target fitted with small pieces of Cr, before capping with a 30 nm thick Cu top layer. During deposition, a magnetic field of about 200 Oe was applied in the film plane and perpendicular to the wedge direction to establish the unidirectional anisotropy.[18] The wedged samples were cut into many small pieces along the wedge direction and individually measured by VSM at room temperature. MOKE measurements were also made by directing the laser beam with a sampling area

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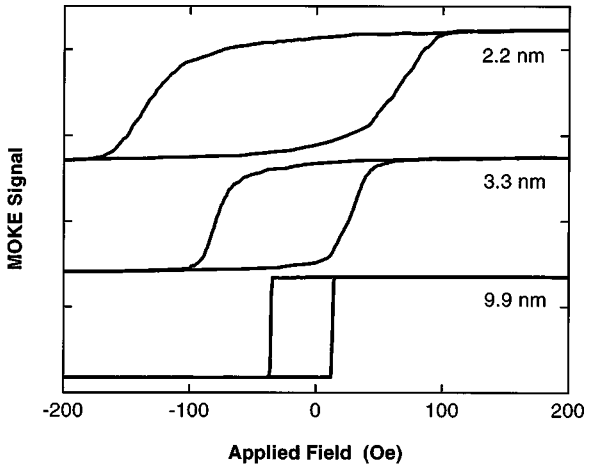

FIG. 1. Representative hysteresis loops at 300 K of Py(t_{FM})/$Cr_{82}Al_{18}$(53 nm) bilayers with different Py thicknesses.

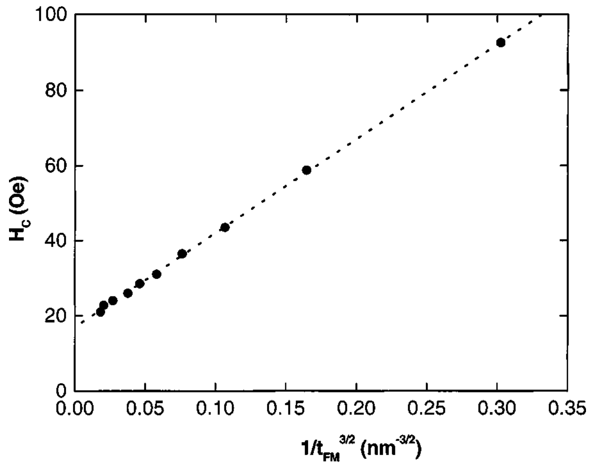

FIG. 3. The dependence of the coercivity at 300 K for Py(t_{FM})/$Cr_{82}Al_{18}$(53 nm) as a function of $1/t_{FM}^{3/2}$.

of about 1 mm^2 at various points on a large uncut wedged sample.

Some representative hysteresis loops of the samples with different FM layer thickness in the series of samples Py(d)/$Cr_{82}Al_{18}$(53 nm) measured by MOKE are shown in Fig. 1. Each hysteresis loop is characterized by an exchange field H_E, coercivity H_C, and the width (ΔH) of switching from $+M$ to $-M$. The values of H_E, H_C, and ΔH increase with decreasing Py thickness. Of those, the increase of ΔH is particularly noticeable. While loops for t_{FM} of about 4 nm are square, the ones at 3 nm and less are considerably slanted, as shown in Fig. 1. The more rapid increase in ΔH with decreasing t_{FM} in Py/CrAl is one of several features that is distinctly different from those in Py/FeMn.

The dependence of H_E on the Py layer thickness at room temperature is shown in Fig. 2 as a function of $1/t_{FM}$ to highlight the fact that H_E exhibits the $1/t_{FM}$ dependence. The exchange coupling energy per unit area is $H_E t_{FM} M_{FM}$, for which we have obtained the value of 4.7×10^{-3} erg/cm^2, using M_{FM}=780 emu/cm^3 for Py. The value of 4.7×10^{-3} erg/cm^2 of Py/CrAl at room temperature is more than one order smaller than those of Py/FeMn at room temperature and Py/CoO at 80 K.[10]

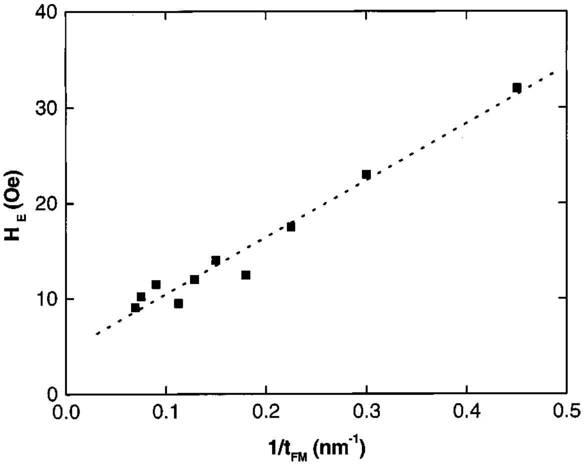

FIG. 2. The dependence of the exchange field at 300 K for Py(t_{FM})/$Cr_{82}Al_{18}$(53 nm) as a function of $1/t_{FM}$.

In Py/CoO and Py/FeMn bilayers, H_C varies as $1/t_{FM}$ at high temperatures but varies as $1/t_{FM}^{3/2}$ at low temperatures. For example, in Py/CoO, H_C varies as $1/t_{FM}^{3/2}$ at $T<90$ K, but as $1/t_{FM}$ at $T>160$ K. The $1/t_{FM}^{3/2}$ dependence has been accounted for by a random-field model by Zhang *et al.*[15] In the present case of Py/CrAl, however, H_C has a $1/t_{FM}^{3/2}$ dependence at *room temperature*, as shown in Fig. 3. The extended temperature range in which the $1/t_{FM}^{3/2}$ dependence is valid, is likely the result of a much weaker exchange coupling in Py/CrAl as mentioned above. It is noted in Figs. 2 and 3 that, when extrapolated to $t_{FM}\rightarrow\infty$, the values of H_E and H_C are small but not zero. This suggests that the $1/t_{FM}$ and the $1/t_{FM}^{3/2}$ dependencies are applicable only for reasonably small values of t_{FM} and cannot be extended to arbitrarily thick FM layers.

Focusing now on the decreasing half of the hysteresis loops shown in Fig. 1, the switching of magnetization from $+\mathbf{M}$ to $-\mathbf{M}$ for each sample with a specific FM thickness occurs *sequentially*. For example, at $H=-70$ Oe, the magnetization of FM layers with $t_{FM}>4.44$ nm has already switched to $-\mathbf{M}$, whereas those with $t_{FM}<4.44$ nm with $+\mathbf{M}$ have not. Therefore, at $H=-70$ Oe, the samples with $t_{FM}>4.44$ nm and $t_{FM}<4.44$ nm belong to *two* macroscopic domains separated by *one* 180° wall. This unique domain structure is formed by capitalizing the inverse dependence of H_E and H_C on t_{FM}. As one changes the magnetic field, the domain wall sweeps across the wedged FM layer along the wedge direction. These features are qualitatively similar to those observed in wedged Py/uniform FeMn bilayers.[18]

In this case of two domains with one wall, the width ΔH in the hysteresis loops is the field range within which the domain sweeps across the sampling area in MOKE measurements, or the width of the individual sample in VSM measurements. As shown in Fig. 2, the value of ΔH becomes larger for smaller t_{FM}, indicating that the rate of motion of the wall (dx/dH) along the wedge direction becomes progressively smaller for thinner FM layers.

The dependence of H_E and H_C at room temperature on the AF thickness t_{AF} is shown in Fig. 4. It has been previ-

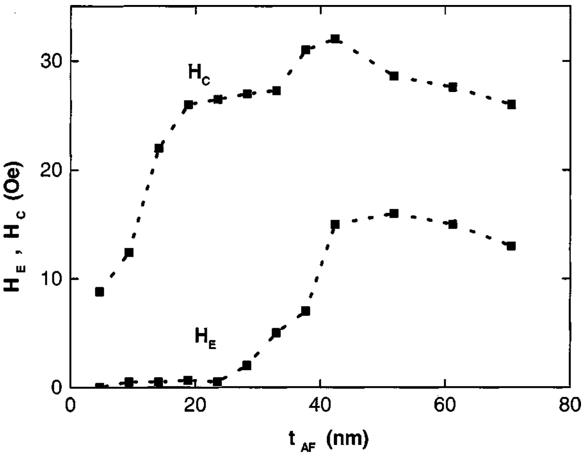

FIG. 4. The values of exchange field and coercivity at 300 K for Py(8 nm)/$Cr_{82}Al_{18}$(t_{AF}) as a function of t_{AF}.

ously shown that as t_{AF} is reduced to less than about 10 nm, the Néel temperature T_N of the AF layer decreases from the bulk value because of finite-size effects, resulting in a reduction of the exchange coupling.[16,17] As shown in Fig. 4, the value of H_C begins to decrease at $t_{AF} \approx 20$ nm, and rapidly so at $t_{AF} < 20$ nm. This behavior, similar to those observed in Py/CoO and Py/FeMn, is expected from finite-size effects. However, the behavior of H_E, also shown in Fig. 4, is different. The values of H_E are not expected to decrease until $t_{AF} < 20$ nm due to an appreciable reduction of T_N, and yet H_E begins to decrease at $t_{AF} \approx 40$ nm, and moreover, H_E vanishes at a critical thickness $(t_{AF})_c \approx 25$ nm below which there is no H_E at room temperature. The different behaviors of H_E and H_C indicate that exchange coupling exists for $t_{AF} < 40$ nm but exchange bias cannot be sustained and eventually vanishes at $(t_{AF})_c \approx 25$ nm. It is well-known that exchange bias relies on the fact that there is a sufficiently large anisotropy constant (K_{AF}) in the AF layer to sustain the reversal of the FM layer. Exchange bias can no longer exist when $K_{AF}t_{AF}$ becomes small compared with the exchange coupling energy. One can estimate the value of K_{AF} of $Cr_{82}Al_{18}$ by comparing the exchange coupling energy per area of 4.7×10^{-3} erg/cm^2 obtained earlier with $K_{AF}(t_{AF})_c$, from which one obtains $K_{AF} = 1.9 \times 10^3$ erg/cm^3.

In summary, in Py/CrAl bilayers using wedged FM and AF layers, we have observed the $1/t_{FM}$ and the $1/t_{FM}^{3/2}$ dependence for the exchange field and coercivity, respectively, at room temperature. The latter is due to a small exchange coupling energy in Py/CrAl. The dependence of the exchange coupling on the AF thickness has also been determined. When the AF thickness is less than 25 nm, exchange coupling remains but without an exchange field when the anisotropy constant in the CrAl layer cannot sustain exchange bias. Switching with two macroscopic domains has also been observed due to the wedged Py layer.

ACKNOWLEDGMENT

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