Title
Dependence of exchange coupling in permalloy/Cr82Al18 bilayers on the constituent layer thickness

Permalink
https://escholarship.org/uc/item/23r9w3wm

Journal
Journal of Applied Physics, 87(9)

ISSN
0021-8979

Authors
Zhou, SM
Liu, Kai
Chien, CL

Publication Date
2000-05-01

DOI
10.1063/1.372802

Peer reviewed
Dependence of exchange coupling in permalloy/Cr$_{82}$Al$_{18}$ bilayers on the constituent layer thickness

S. M. Zhou, Kai Liu, and C. L. Chien

Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, Maryland 21218

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.

A great deal of attention has recently been focused on the ferromagnetic (FM)/antiferromagnetic (AF) exchange coupling because of the intriguing phenomena and applications in spin-valve giant magnetoresistance devices for sensing magnetic fields. 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. The original simple model with a static AF spin structure does not account for the observed characteristics. 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, has been indicated by a number of recent micromagnetic calculations.

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. The exchange field generally decreases as temperature approaches the so-called blocking temperature $T_B$. 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. 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, among 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 $1/t_{FM}^{3/2}$ (where $t_{FM}$ is the FM layer thickness) at high temperatures, but shows a $1/t_{FM}^{3/2}$ dependence at low temperatures. 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. However, for relatively large values of $t_{AF}$, the observed dependence is probably a manifestation of the domain structure in the AF layers.

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 $1/t_{FM}^{3/2}$ dependence of $H_E$ and $H_C$, switching in wedged FM/uniform AF bilayers involves only two macroscopic domains separated by one domain wall.

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 $1/t_{FM}^{3/2}$ 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. 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...
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 ($\Delta H$) of switching from $+M$ to $-M$. The values of $H_E$, $H_C$, and $\Delta H$ increase with decreasing Py thickness. Of those, the increase of $\Delta H$ 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 $\Delta H$ 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 $4.7 \times 10^{-3}$ erg/cm$^2$, using $M_{FM} \approx 780$ emu/cm$^3$ for Py. The value of $4.7 \times 10^{-3}$ 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.$^{10}$

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 $+M$ to $-M$ 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 $-M$, whereas those with $t_{FM}<4.44$ nm with $+M$ 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 wedge 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 $\Delta H$ 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 $\Delta H$ 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-
The values of exchange field and coercivity at 300 K for Py(8 nm)/Cr$_{82}$Al$_{18}$ as a function of $t_{AF}$.

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

It is no Hall coupling energy. One can estimate the value of $t_{AF}$ at the Neél temperature and anisotropy constant ($K_{AF}$) from which one obtains $K_{AF} = 1.9 \times 10^3$ erg/cm$^2$.

In summary, in Py/Co layers using wedge FM and AF layers, we have observed the $1/t_{FM}$ and the $1/t_{AF}^{3/2}$ dependence for the exchange field and coercivity, respectively. At room temperature, the latter is due to a small exchange coupling energy in Py/Co. 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

This work has been supported by NSF Grant Nos. DMR96-32526 and DMR97-32763.