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Coercivity enhancement in exchange-biased ferromagnet/FeMn bilayers

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Co-Ni/FeMn bilayers with various Co-Ni compositions and ferromagnet/FeMn bilayers with ferromagnetic materials Ni, permalloy, $Ni_{50}Fe_{50}$, Co, and Fe were prepared. For these series, the coercivity of the exchange coupled bilayers and the anisotropy properties of corresponding free ferromagnetic layers are correlated to each other. The coercivity enhancement is found to be larger for ferromagnetic layers with larger intrinsic magnetic anisotropy.

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If an antiferromagnet (AFM)/ferromagnet (FM) bilayer is cooled from above the Neél temperature of the AFM layer to low temperature in the presence of an external magnetic field, the hysteresis loop of the pinned FM layer will be shifted from the zero field.[1–5] At the same time, the coercivity of the exchange-biased bilayers is usually enhanced, compared to the corresponding free FM layer. The dependencies of the so-called exchange field on the constituent layer thickness and temperature have been studied extensively and are well understood. For example, the exchange field is usually inversely proportional to the FM layer thickness when it is larger than 3.0 nm.[3,6] Because the coercivity enhancement is strongly related to the asymmetrical magnetization reversal during the variation of the external field, the associated phenomenology can provide important information about the origin of the exchange coupling.[7–10]

The dependence of the coercivity on the constituent layer thickness has been studied in FM/AFM bilayers. For example, the coercivity of permalloy(Py)/CoO and Py/CrAl bilayers is a linear function of $1/t_{\mathrm{FM}}^{3/2}$ (t_{FM} is the FM layer thickness).[11,12] For Py/FeMn($Fe_{50}Mn_{50}$) bilayers, the coercivity is a linear function of $1/t_{\mathrm{FM}}$, suggesting the interfacial nature of the exchange coupling.[13] In order to explain the mechanism of the coercivity enhancement, several models have been proposed.[10,14–17] In these models, the enhancement was assumed to be related to the microscopic exchange constants in FM and AFM layers and that between the first AFM and FM atomic planes at the interface, the grain size distributions of the AFM and FM layers, and even the anisotropic constant of the AFM layer. However, the understanding of the coercivity enhancement in FM/AFM bilayers remains unsatisfactory. To our knowledge there has been no experimental report about the dependence of the coercivity enhancement on the intrinsic properties of constituent FM layers. In above theoretical models, the intrinsic anisotropy of the FM layer has been disregarded in the explanations of the coercivity enhancement.

In order to emphasize this issue, we have prepared various wedged-FM/FeMn(15.0 nm) bilayers with FM materials Ni, Py, $Ni_{50}Fe_{50}$, Co, and Fe. The details of sample preparation will be described below. As shown in Fig. 1, the exchange coupling energy $\Delta\sigma$ changes monotonically with the FM magnetization. For example, $\Delta\sigma$ of Ni/FeMn bilayers is smaller than that of Fe/FeMn bilayers. However, the slope of the curve for $H_{\mathrm{C}} \propto 1/t_{\mathrm{FM}}$ does not change monotonically with the FM magnetization. This might be due to different crystal structures and the especially magnetic anisotropy of various FM materials.

Because the exchange bias is sensitive to the interface topology and the crystal structures of the FM and AFM layers, it is essential that both the FM and AFM materials share the same crystal structure and the same crystalline orientation. The Co-Ni/FeMn layer is a perfect example for this purpose, in which the Co-Ni alloys and FeMn share the same fcc(111) orientation with close lattice constants. Upon varying the composition of the Co-Ni alloys, the magnetocrystalline anisotropy constant can be manipulated to exhibit its effect on the coercivity enhancement.[18] The topology of the FM/AFM interface and the microstructure of the AFM layer

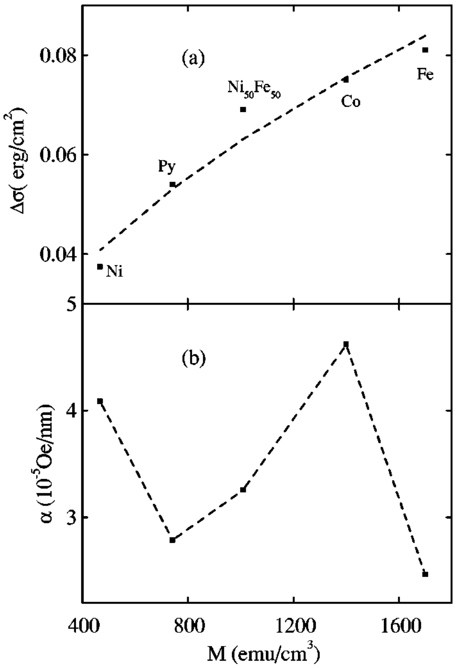

FIG. 1. The dependencies of the exchange coupling energy (a) and the slope (b) on the FM magnetization for various wedged-FM/FeMn(15.0 nm) bilayers with FM materials Ni, Py, $Ni_{50}Fe_{50}$, Co, and Fe, where α is the slope of the curve $H_C \propto 1/t_{\mathrm{FM}}$. The exchange coupling energy was deduced from the slope of the curve $H_E \propto 1/t_{\mathrm{FM}}$. The dashed line in (a) is the fitted result.

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change little with variation of the FM composition. Here FeMn is a perfect AFM material, in which the coercivity changes as a linear function of both the inverse FM layer thickness and the temperature.[4,5] In this paper, we will study the effect of the intrinsic anisotropy of the FM layers on the coercivity enhancement of exchange biased bilayers, including Co-Ni/FeMn bilayers with various FM compositions and FM/FeMn bilayers with FM materials Ni, Py, $Ni_{50}Fe_{50}$, Co, and Fe.

A large specimen of the Co_xNi_{100-x}/FeMn bilayer was made on a Si(100) substrate by a multisource sputter deposition system. A 15.0-nm-thick FeMn layer was deposited from an alloy FeMn target onto a Cu buffer layer of 30.0 nm thick to promote the growth of (111)-oriented fcc AFM FeMn. The Co-Ni alloy was made by codeposition from two separate sources of Co and Ni, such that there is a composition gradient across a length of approximately 10 cm, and that the magnetization M_{FM} of the Co-Ni alloys is an approximately linear function of the sampling location along the direction of the composition gradient. Finally, the multilayer was capped with a 30.0-nm-thick Cu film to avoid oxidation. The details of the dependencies of the thickness and magnetization of the FM layer on the sampling location have been described elsewhere.[19] The large specimen was then cut into many small samples along the gradient direction before the field-cooling process. Each sample was separately cooled from 170 °C to room temperature in a 0.5-T magnetic field perpendicular to the composition gradient direction. For comparison, a corresponding free Co_xNi_{100-x} layer was deposited onto 30-nm-thick Cu layer. The various wedged-FM/FeMn bilayers with FM materials Ni, Py, $Ni_{50}Fe_{50}$, Co, and Fe, were deposited from corresponding targets. The details of the sample preparation and the field cooling have been described elsewhere.[13]

Figure 2(a) shows the dependence of the exchange coupling energy $\Delta\sigma$ in Co-Ni/FeMn bilayers on the Co_xNi_{100-x} composition. $\Delta\sigma$ is found to increase with increasing Co composition as well as the FM magnetization, which can be obtained approximately by averaging the magnetizations of Co and Ni components. According to the relation $H_E t_{\mathrm{FM}} M_{\mathrm{FM}} = \Delta\sigma$, H_{E} is found to decrease monotonically with M_{FM}. Comparing the results in Figs. 1(a) and 2(a), one can find that $\Delta\sigma$ increases with increasing FM magnetization for both Co-Ni/FeMn and other FMs/FeMn bilayers, scaling as a linear function of $\sqrt{M_{\mathrm{FM}}}$. This means that the FM magnetization plays a major role in the exchange coupling energy. However, their coefficients are different from each other in Figs. 1(a) and 2(a), due to different crystal structures of various FM materials in Fig. 1(a). It is noted that the exchange coupling energy has also been found to depend on M_{FM} in CoO-based bilayers.[20]

Figure 2(b) shows the dependence of the coercivity on the FM composition in Co-Ni/FeMn bilayers. In comparison, the coercivity of the free Co-Ni layer is also given. The coercivities of Co-Ni/FeMn bilayers and free Co-Ni layer synchronously increase with increasing Co-Ni composition, and have a maximum at the same composition. At the composition of Co_xNi_{100-x}, the coercivity of the bilayers and the single free layer is smallest and then increases with increasing Co content. Apparently, they are correlated to each other. For FM/FeMn bilayers, the coercivity obeys the empirical formula $H_C = H_C(0) + \alpha/t_{\mathrm{FM}}$, where $H_C(0)$ refers to the coercivity of corresponding free FM layers and is independent of the FM thickness, and the second term at the right side arises from the exchange coupling and is proportional to the inverse FM layer thickness. This linear dependence was observed in Fe/FePd bilayers.[21] In this way, the parameter α can be used to express the coercivity enhancement in FM/FeMn bilayers. For Co-Ni/FeMn bilayers, the variation of the parameter with Co-Ni composition is shown in Fig 2(c). Apparently, α has a maximum near 50-at % Co, where the coercivity of the free Co-Ni layer has a maximum value.

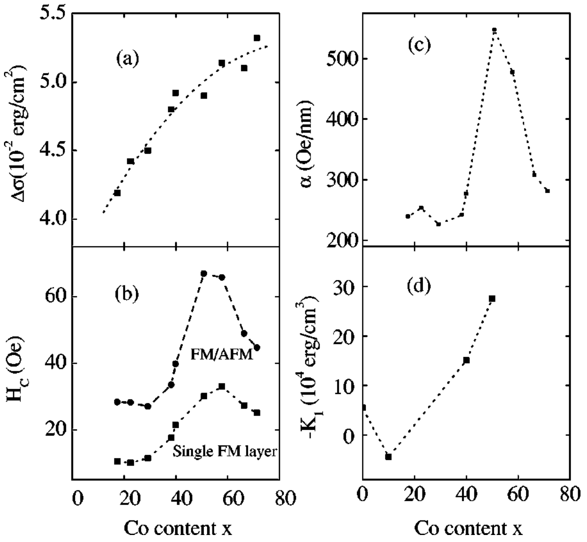

FIG. 2. The FM composition dependencies of the exchange coupling energy (a), the coercivity (b), the slope of the coercivity in Co_xNi_{100-x}(15 nm)/FeMn(15 nm) bilayers (c), and the first order anisotropy constant K_1 of Co_xNi_{100-x} alloys (d) (Ref. 18). In comparison, the coercivity of the Co_xNi_{100-x} single layer on Cu buffer is also given in (b). The dashed line in (a) is the fitted result.

Several factors, such as the interfacial exchange coupling energy and the grain size of the FM layer, are considered to have influences on the coercivity enhancement.[14,15] It is noted that the lattice constant of Co-Ni alloys changes by as small as 0.4% in the studied composition range.[22] Thus the grain size changes little with the FM composition. Therefore, the change of the FM crystal structure cannot account for the coercivity behavior. Second, as theoretical work shows, since the coercivity of FM/AFM bilayers increases monotonically with a variation of the exchange coupling energy,[14] the effect of the exchange coupling energy can be excluded in the explanation of the nonmonotonic variation of the coercivity.

One can find that the coercivity enhancement in Co-Ni/FeMn bilayers is correlated with the coercivity of the free Co-Ni layer, as shown in Figs. 2(b) and 2(d). Therefore, the coercivity enhancement in the bilayers is related to the intrinsic anisotropy of the Co-Ni layer. Because of the negligible change of the lattice constant with alloying composition, the magnetoelastic contribution can be neglected. The variation of the coercivity with the alloying composition mainly arises from the magnetocrystalline anisotropy in the free Co-Ni layer. Fortunately, one can find that the first order anisotropy constant of the polycrystalline Co-Ni alloys has a variation similar to the coercivity enhancement of the FM/AFM bilayers,[18] as shown in Fig. 2(d). Near the composition of $Co_{20}Ni_{80}$, where the Co-Ni layer is magnetically soft, the parameter α is small. At large Co contents, where the Co-Ni layer becomes magnetically hard, the slope α is very large. Therefore, the coercivity enhancement of the pinned FM layer is related to the intrinsic magnetocrystalline anisotropy as a function of alloying composition. This is also true in Fig. 1(b). The slope is FM material dependent. Py and $Ni_{50}Fe_{50}$ alloys, and pure Ni all have fcc structures. In the sequence of Py, $Ni_{50}Fe_{50}$, and Ni, the magnitude of the magnetocrystalline anisotropy is $0,1.0\times 10^4$ and 6×10^4 erg/cm^3, respectively.[23] Obviously, the slope α increases with increasing anisotropy constant of corresponding free FM layers. Therefore, the magnetic anisotropy of FM layers influences not only the first term $H_C(0)$ but also the slope of second term α. It is well known that the FM domain structure is strongly influenced by the magnetic anisotropy. During the FM magnetization reversal, the domain wall in the FM layers penetrates into AFM layers and a hybrid FM/AFM domain wall is formed.[8,24] The coupling between domain walls in neighboring layers has been suggested to play an important role in the coercivity variation of soft/hard layered structures.[25] So the anisotropy of free FM layers influence the coercivity enhancement through both inhomogeneous FM and irreversible AFM domain reversals.[10] This will stimulate further theoretical work to study the coercivity enhancement of FM/AFM bilayers.

In summary, the coercivity of the FM/AFM bilayers is correlated to the magnetic anisotropy of the corresponding FM layer films in Co-Ni/FeMn bilayers with varying FM compositions and FM/FeMn bilayers with FM materials Ni, Py, $Ni_{50}Fe_{50}$, Co, and Fe. The coercivity enhancement of the exchange-coupled FM/AFM bilayers changes with the magnetic anisotropy of the FM layers. This work will possibly shed light on the mechanism of the exchange bias. In the practical applications of exchange bias for giant magneto resistance devices, it is desirable to have a small H_C and a large H_E. Hence one should use a FM layer, which has a small magnetic anisotropy constant and magnetization.

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