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Longitudinal and perpendicular exchange bias in FeMn/(FeNi/FeMn)$_n$ multilayers

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Exchange bias in ferromagnetic (FM)/antiferromagnetic (AF) bilayers is usually investigated in the longitudinal configuration with the exchange coupling established in the film plane. In this work, we report on the perpendicular exchange bias in FeMn(8 nm)/[FeNi(2 nm)/FeMn(8 nm)]$_n$ multilayers induced by perpendicular field cooling. The thin FeNi layers give rise to large values of the exchange field and coercivity, and $n=15$ allows a sufficiently large magnetization for the measurements. Even though the soft FeNi layers have an intrinsic in-plane anisotropy, perpendicular exchange bias has been observed after cooling in a perpendicular external field. The exchange field in the perpendicular configuration is about 0.85 that of the longitudinal case. In both the longitudinal and perpendicular configurations, the exchange field decreases quasilinearly with temperature. The squareness of perpendicular hysteresis loops decreases with increasing temperature. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1544447]

When ferromagnetic (FM)/antiferromagnetic (AF) bilayers are cooled in an external magnetic field from above the Néel temperature of the AF layer, both unidirectional exchange anisotropy and uniaxial magnetic anisotropy are induced at the FM/AF interface, resulting in a shifted hysteresis loop and a coercivity enhancement. Longitudinal exchange coupling has been explored in a wide range of materials and structures with in-plane anisotropy.[1–5] Recently, several groups have shown that exchange bias can also be established in multilayers with perpendicular anisotropy.[6–8] Multilayered Co$_x$Fe$_{1-x}$/Pt films show square hysteresis loops when the field is perpendicular to the film plane, indicating that the magnetic easy axis is along the surface normal. The shifted square loops have been obtained when the multilayers are in contact with antiferromagnetic CoO, FeMn, or FeF$_2$ after field cooling.

In contrast to the studies on films with perpendicular anisotropy, no observations of perpendicular exchange biasing have been reported for films with in-plane anisotropy. It is interesting to explore whether perpendicular exchange biasing exists in samples with in-plane anisotropy. In principle, exchange bias can be induced regardless of the field cooling direction, however, it remains to be seen how perpendicular exchange bias is different from the in-plane case.

Here, we report the exchange bias study in NiFe/FeMn multilayers, in which both longitudinal and perpendicular exchange coupling have been observed at room temperature with the cooling field applied along the corresponding directions. The temperature dependence of the perpendicular exchange field and coercivity with perpendicular field cooling has been investigated. Compared to longitudinal field cooling, the perpendicular exchange bias in the NiFe/FeMn multilayers is always smaller than the in-plane values. With decreasing temperature, the squareness of the perpendicular hysteresis loops increases, indicating a stronger perpendicular anisotropy induced by the cooling field.

Samples were fabricated by dc magnetron sputtering in a 6 mTorr Ar atmosphere with a base pressure of 8×10^{-8} Torr. Si wafers with a native oxide layer were used as substrates. Two samples were fabricated: [FeNi(2 nm)/FeMn(8 nm)]$_{15}$ multilayers and Cu(30nm)/FeMn(8 nm)/[FeNi(2 nm)/FeMn(8 nm)]$_{15}$ /Cu(30 nm) multilayers for structural and magnetic measurements, respectively. The second sample includes an extra FeMn (8 nm) layer such that every FeNi (2 nm) layer is sandwiched between two FeMn(8 nm) layers. The bottom Cu layer is included to stabilize the antiferromagnetic γ phase of FeMn and the top Cu layer protects the magnetic layers from oxidation. No external magnetic field was applied during deposition.

Figure 1 shows a small angle x-ray reflectivity pattern for the [FeNi(2 nm)/FeMn(8 nm)]$_{15}$ multilayer sample with Cu $K\alpha$ radiation. Figure 1 clearly shows the superlattice peaks associated with the multilayer structure. The calculated bilayer period of 10.2 nm is in good agreement with the designed period of 10 nm.

The magnetic properties were characterized using a vibrating sample magnetometer [(VSM) ADE model 10] from

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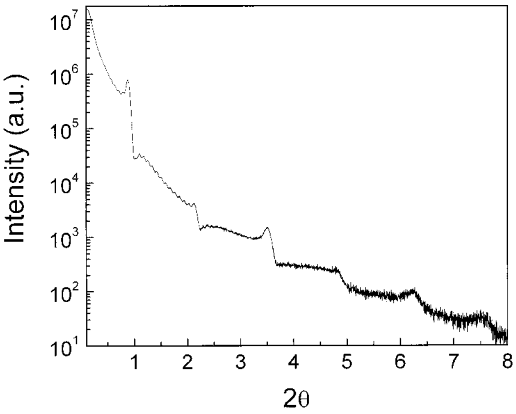

FIG. 1. Small angle x-ray diffraction pattern for [FeNi(2 nm)/FeMn(8 nm)]$_{15}$ multilayers.

100 K to room temperature. Lower-temperature measurements, down to 5 K, were performed on a superconducting quantum interference device (SQUID) magnetometer. All samples were heated to 428 K in the VSM and cooled in a 2.0 T external field. For measurements taken between 5 and 100 K, the sample was first field cooled to room temperature in the VSM and then field cooled in the SQUID magnetometer. At each temperature, the sample was cycled four times in the external field and the fifth hysteresis loop was recorded.

The FeMn(8 nm)/[FeNi(2 nm)/FeMn(8 nm)]$_{15}$ sample was first cooled with the field applied parallel to the film plane. Measurements were taken with the applied field parallel and perpendicular to the film. Figure 2(a) shows a room-temperature hysteresis loop with longitudinal field cooling and measured along the cooling field direction. An exchange bias field of −824 Oe and a coercivity of 238 Oe were measured. Note that the multilayer structure enables high accuracy measurements even though the NiFe layers are only 2 nm thick. The multilayer structure is particularly advantageous for studying perpendicular exchange bias in small magnetic fields where the signal is even smaller. In addition, the multilayer structure also provides exchange coupling from both interfaces of the FM layer as opposed one interface in FM/AF bilayers.

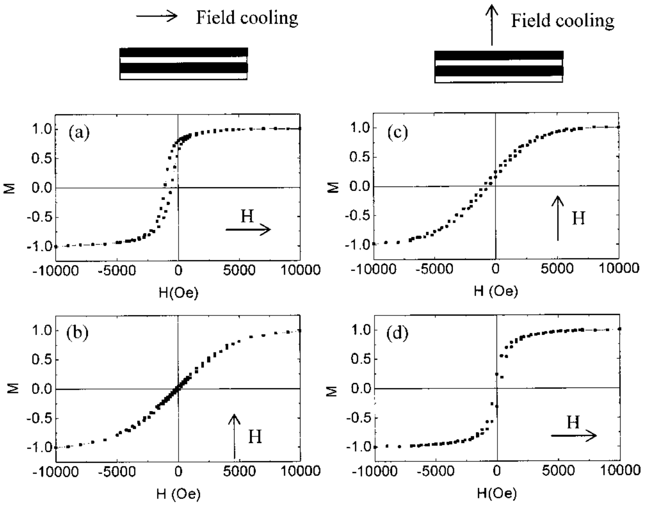

FIG. 2. Hysteresis loops of FeMn(8 nm)/[FeNi(2 nm)/FeMn(8 nm)]$_{15}$ multilayers. (a) and (c) longitudinal field cool, (b) and (d) perpendicular field cool.

The longitudinal exchange energy per unit area ($\Delta\sigma_{\parallel}$) of the FeMn(8 nm)/[FeNi(2 nm)/FeMn(8 nm)]$_{15}$ multilayer can be calculated from:

$$\Delta\sigma_{\parallel} = -H_{E\parallel} t_F M_S / 2, \tag{1}$$

where $H_{E\parallel}$ is the measured exchange field, t_F is the single FM layer thickness, M_s is the saturation magnetization of the FM layer, and the factor of 2 is due to the two FM/AF interfaces. For the FeMn(8 nm)/[FeNi(2 nm)/FeMn(8 nm)]$_{15}$ multilayer sample $\Delta\sigma_{\parallel}$ has been calculated to be 0.065 erg/cm^2 using $M_s = 785$ emu/cm^3 at room temperature.

When the longitudinally field cooled sample was measured with the field perpendicular to the film plane, as shown in Fig. 2(b), we observed a slanted loop, characteristic of a magnetic hard axis. As expected, there is no exchange bias field since the exchange coupling has been established in the film plane.

The same [FeNi(2 nm)/FeMn(8 nm)]$_{15}$ multilayer sample was then cooled with the applied field perpendicular to the film plane from 428 to 300 K. After perpendicular field cooling, the hysteresis loop is shifted with an exchange bias field of −676 Oe and coercivity of 203 Oe, as shown in Fig. 2(c). This result clearly shows that perpendicular field cooling has established perpendicular exchange bias even though it is the hard axis of the thin ferromagnetic layers. When the perpendicular exchange-coupled sample is measured with the field in the film plane, there is no loop shift but enhanced coercivity, as shown in Fig. 2(d).

A comparison of the four hysteresis loops in Fig. 2 shows that the values of exchange bias field H_E and the coercivity H_C at room temperature for longitudinal exchange bias are larger than those for perpendicular exchange bias. Figure 3 shows the temperature dependence of the coercivity and the exchange field for both longitudinal and perpendicular field cooling. Both the coercivity H_C and the absolute value of exchange bias field H_E display similar temperature dependences regardless of the field cool direction. The longitudinal and the perpendicular exchange bias fields show a quasilinear temperature dependence and extrapolate to zero at 424 and 410 K, respectively. At each temperature, the perpendicular exchange bias field is always smaller than the longitudinal exchange bias field, however, the ratio of the perpendicular exchange bias field to the longitudinal exchange field remains at about 0.85 with a weak temperature dependence, as shown in Fig. 4. The coercivity H_c shows a much stronger temperature dependence than the exchange bias field and decreases rapidly with temperature. The value of H_C for the perpendicular exchange bias is also always smaller than that for the longitudinal exchange bias.

For the case of perpendicular exchange bias in Co/Pt multilayers pinned by CoO,[7] the perpendicular exchange bias field was also found to be smaller than the longitudinal exchange bias field with a ratio of about 0.5. This fact has been attributed to the special spin structure and the strong crystalline anisotropy of (111) texture of CoO. Unlike CoO and

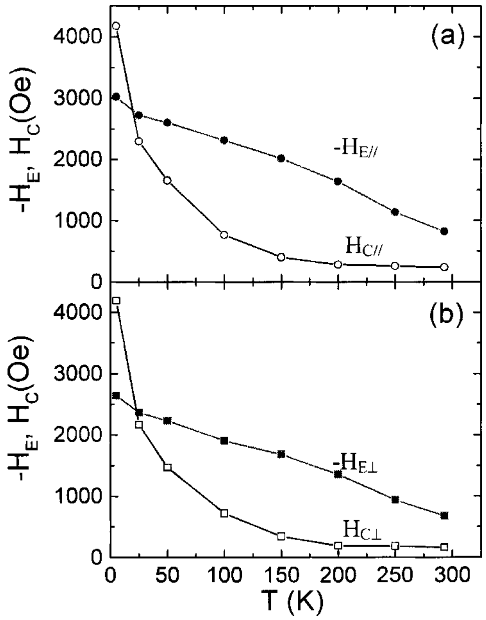

FIG. 3. Temperature dependence of the exchange bias and coercivity for longitudinal (a) and perpendicular (b) field cool.

FeF_2 used in the perpendicular anisotropic multilayers,[6–8] FeMn does not have a bulk spin structure with alternating oppositely aligned spins. Antiferromagnetic γ-FeMn has a face-centered-cubic structure where the Fe and Mn atoms randomly occupy the lattice.[9,10] FeMn has a noncollinear spin structure and the crystalline anisotropy is much smaller than that of CoO. These differences probably cause the ratio of the exchange bias field in FeMn/FeNi multilayers to be different from those in other systems.

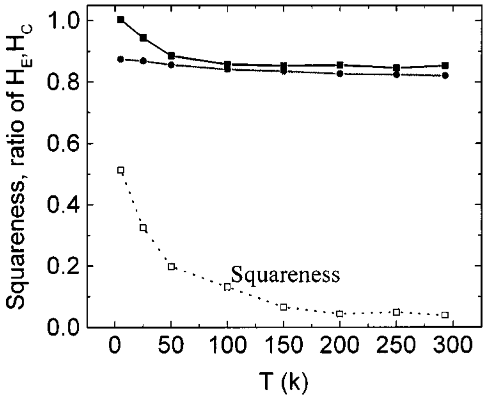

FIG. 4. Ratios of exchange bias field and coercivity for perpendicular and longitudinal field cool in FeMn(8 nm)/[FeNi(2 nm)/FeMn(8 nm)]$_{15}$ multilayers as a function of temperature (solid line). Also shown is the temperature dependence of the hysteresis loop squareness for perpendicular exchange bias (dotted line).

A comparison of Figs. 2(c) and 2(d) show that even though perpendicular exchange bias has been established, there remains substantial in-plane magnetic anisotropy. Indeed, the magnetization saturates at a smaller field with the field applied in-plane than when applied perpendicular to the film plane. It is also noted that the squareness of the hysteresis loop in both Figs. 2(c) and 2(d) is small. For the unshifted loop in Fig. 2(d), the squareness is taken as the ratio of remanent magnetization and saturation magnetization. For the shifted loop in Fig. 2(c), the remanent magnetization is taken as the value at H_E. While perpendicular squareness in Fig. 2(c) is small, its value increases rapidly with decreasing temperature at low temperatures as shown in Fig. 4, in a manner similar to the temperature dependence of the coercivity. The remanence becomes quite substantial (about 0.5) at low temperatures. This suggests that if thinner FM layers had been used, one may achieve perpendicular exchange bias with perpendicular anisotropy.

In summary, we have shown that perpendicular exchange bias can be established in FM/AF multilayers with in-plane anisotropy through perpendicular field cooling. In the FeMn(8 nm)/[FeNi(2 nm)/FeMn(8 nm)]$_{15}$ multilayer, the perpendicular exchange bias field is about 0.85 of the longitudinal exchange bias field at all temperatures. Although in-plane magnetic anisotropy remains after perpendicular field cooling, the rapidly increasing squareness with decreasing temperature, suggests that perpendicular anisotropy may be possible with different ferromagnetic layers with small thicknesses.

ACKNOWLEDGMENT

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