Anomalous training effect of perpendicular exchange bias in Pt/Co/Pt/IrMn multilayers

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For perpendicularly magnetized Pt/Co/Pt and Pt/Co/Pt/IrMn multilayers, the magnetization reversal process is accompanied by the pinned domain wall motion. For Pt/Co/Pt/IrMn multilayers, the asymmetry of hysteresis loops is always equal to zero and the exchange field \( H_E \) decreases during consecutive hysteresis loops. It is interesting to find that the variation in \( H_E \) with the cycle number \( n \) cannot be fitted by the empirical \( 1/\sqrt{n} \) function. Meanwhile, the coercivity almost does not change. The unique feature of the training effect is caused by the magnetization reversal mechanism of the pinned domain wall motion in the Pt/Co/Pt multilayers. © 2008 American Institute of Physics. [DOI: 10.1063/1.3039059]

As a well known phenomenon, exchange bias (EB) in ferromagnet (FM)/antiferromagnet (AFM) bilayers has received much attention because of its abundant applications in magnetoelectronic devices. In the EB effect, the center of the hysteresis loop is shifted along the magnetic field axis by an amount of the exchange field \( H_E \). Meanwhile, the coercivity \( H_C \) is often increased, in comparison with that of the corresponding FM layer. Among EB-related phenomena, the training effect has been neglected in both experiments and theories. In most studies of the EB training effect, the magnetization reversal process in FM/AFM bilayers is accompanied by domain rotation. The mechanism of the EB training effect still remains unclear when the magnetization reversal process is accompanied by pinned domain wall motion. It is noted that in perpendicularly magnetized ultrathin films, the pinned domain wall motion often occurs. In this letter, we have studied the EB training effect in the case of pinned domain wall motion by using perpendicularly magnetized Pt/Co/Pt/IrMn multilayers. A new feature of the EB training effect is observed that \( H_E \) shows a prominent training effect whereas \( H_C \) almost does not change with the cycle number \( n \).

A large specimen of the Pt(3 nm)/Co(0.5 nm)/Pt(0.5 nm)/Ir\(_{25}\)Mn\(_{75}\) (IrMn) sample was deposited on a glass substrate by magnetron sputtering at ambient temperature, where the IrMn layer thickness takes a wedge shape to avoid the run-to-run error. A uniform Pt(3 nm)/Co(0.5 nm)/Pt(0.5 nm)/IrMn (4 nm) multilayer was also prepared. The base pressure of the system was \( 2 \times 10^{-5} \) Pa and the Ar pressure 0.40 Pa during deposition. A magnetic field of about 250 Oe was applied normal to the film plane in order to establish the perpendicular EB. Components of magnetic moment parallel and perpendicular to the external magnetic field, \( m_x \) and \( m_y \), were recorded simultaneously by vector vibrating sample magnetometer of model 7407 from LakeShore Co. All measurements were performed at room temperature.

Figure 1 demonstrates typical out-of-plane hysteresis loops of the uniform Pt(3 nm)/Co(0.5 nm)/Pt(0.5 nm)/IrMn(4 nm) sample with \( n = 1, 2, \) and 30. Apparently, the perpendicular EB is well established. \( H_E/H_C \) are 289/265, 257/254, and 131/247 in the unit of oersted for \( n = 1, 2, \) and 30, respectively. Two distinguished characteristics can be found. First, \( H_E \) decreases greatly with \( n \). After consecutive hysteresis loops of \( n = 30, H_E \) is reduced by more than 50%. In contrast, \( H_C \) does not change much. During subsequent measurements, the coercive fields of both the descent and the ascent branches move toward the positive magnetic field direction. Remarkably, the amount of the magnetic field shift for the ascent branch is almost equal to that of the descent branch. Second, for the present Pt/Co/Pt/IrMn multilayers, the asymmetry of hysteresis loops is always equal to zero during subsequent measurements because \( m_x \) near the coercive fields almost equals zero too. It is quite different...
from the conventional results in which the asymmetry changes greatly after the first magnetization reversal. Figure 2(a) shows the dependence of $H_E$ and $H_C$ on $n$. $H_E$ decreases gradually with increasing $n$. It can be fitted by an exponential function $H_E(n)/H_E(1) = p + qe^{-n}$. The solid line in (a) refers to the fitted results by an exponential function $H_E(n)/H_E(1) = p + qe^{-n}$, where $p$, $q$, and $n0$ are parameters.

The pinned domain wall motion during the magnetization reversal process has also been observed in the longitudinal EB, in which the pinning sites are located at the boundary between neighboring AFM domains. For the present Pt/Co/Pt/IrMn multilayers, however, the pinning sites are located inside the FM multilayer because the magnetization reversal in the pure FM multilayer is also accompanied by the pinned domain wall motion. The domain wall energy $\gamma$ includes contributions from that of the FM layer and the interfacial one, corresponding to the intrinsic coercivity of the FM layer and the coercivity enhancement caused by the EB, respectively. Therefore, $H_C = (1/M_{FMax})\langle(\partial M/\partial x)\rangle_{Max}$. Since AFM spins of rotatable and nonrotatable grains in the polycrystalline AFM layer undergo transitions from nonequilibrium to equilibrium states during consecutive measurements, the average value of the area exchange coupling energy decreases during subsequent measurements of hysteresis loop, leading to the reduction in $H_E$. On the other hand, the induced “perpendicular uniaxial anisotropy” and $H_K$ are reduced. Since the uniaxial anisotropic field is much larger than that of the pinning field at $\theta_H = 0$, the coercivity is determined by the pinning field instead of the perpendicular anisotropy energy. The local inhomogeneity of the interfacial exchange coupling energy may be fixed when it is induced by defects and other ingredients near the nonrotatable AFM grains. Therefore, the coercivity does not change with $n$. For most FM/AFM bilayers, however, the magnetization reversal process is involved by the domain rotation and the coercivity may be reduced during the training effect because it is related to the uniaxial anisotropy. In a word, the training effect of $H_C$ is induced by the pinned domain wall motion during the FM magnetization reversal.

For the Pt/Co/Pt/IrMn multilayers, the variation in $H_E$ with $n$ is suggested to arise from the particular magnetization reversal mechanism. With the pinned domain wall motion, the FM magnetization and the exchange field acting on the AFM spins are always parallel or antiparallel to the initial cooling field direction during consecutive hysteresis loops. Although Binek’s thermodynamics approach has argued that the linear function of $1/\sqrt{n}$ does not depend on the magnetization reversal process, however, the domain rotation often occurs during magnetization reversal process when the empirical law holds experimentally. It is reasonable to assume...
that during the FM magnetization reversal process the AFM spin rotation exists for conventional FM/AFM bilayers and disappears for the present Pt/Co/Pt/IrMn multilayers.\textsuperscript{16} The present training effect of $H_E$ is induced by the unique magnetization reversal mechanism and cannot be explained in terms of Binek’s thermodynamics approach.\textsuperscript{9}

Figure 4 shows the dependence of $H_E(C=1)$ and the training effect on the AFM layer thickness $t_{AFM}$ for the Pt(3 nm)/Co(0.5 nm)/Pt(0.5 nm)/IrMn multilayers. At $t_{AFM} < 3.6$ nm, $H_E(C=1)$ is equal to zero and sharply increases toward saturation with increasing $t_{AFM}$. Meanwhile, $H_C$ acquires a maximum at $t_{AFM}=4.5$ nm. As $t_{AFM}$ is increased, $\Delta H_E/H_E(1)$ goes through a maximum, whereas $\Delta H_C/H_C(1)$ almost does not change. These results can be understood using a simplified thermal activation model.\textsuperscript{17} At small $t_{AFM}$, the energy barrier (the product of the grain volume and the anisotropy constant) is too small to overcome the thermal energy and thus all the AFM grains are in the superparamagnetic state, resulting in zero $H_E$ and small $H_C$ as well as negligible training effect. At the intermediate $t_{AFM}$, some AFM grains become thermally stable, which results in nonzero $H_E$, the enhanced $H_C$, and the prominent training effect of $H_E$. At large $t_{AFM}$, the energy barrier is high enough to overcome the thermal energy, $H_E$ is saturated, and $H_C$ is decreased. At the same time, the shrinkage of $H_E$ is suppressed.

In summary, for the Pt/Co/Pt/IrMn multilayers, the magnetization reversal is accompanied by the pinned domain wall motion and the asymmetry of hysteresis loops always equals zero in the training effect. $H_E$ decreases greatly with increasing $n$. In contrast, $H_C$ almost does not change. Moreover, the variation in $H_E$ with $n$ cannot be described by the empirical law of $1/\sqrt{n}$. It is suggested that the unique feature of the EB training effect is caused by the pinned domain wall motion during the FM magnetization reversal process. This work will stimulate further theoretical investigation of the EB training effect.

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\begin{figure}[h]
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\includegraphics[width=0.8\textwidth]{fig4.png}
\caption{(Color online) For the Pt(3 nm)/Co(0.5 nm)/Pt(0.5 nm)/IrMn multilayers, variations in $H_E$ (solid square) and $H_C$ (solid circle) (a), $\Delta H_E/H_E(1)$ (solid square) and $\Delta H_C/H_C(1)$ (solid circle) (b) with $t_{AFM}$.}
\end{figure}

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