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

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A new characteristic is observed in the training effect of perpendicular exchange bias. For Pt/Co/Pt/IrMn multilayers with perpendicular magnetic anisotropy, the magnetization reversal process is accompanied by pinned domain wall motion and the asymmetry of hysteresis loop is always equal to zero during subsequent measurements. It is interesting to find that the exchange field decreases greatly as a function of the cycling number while the coercivity almost does not change. It is clearly demonstrated that the training effect of perpendicular exchange bias strongly depends on the magnetization reversal mechanism of the ferromagnetic layer.

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As a well known phenomenon, exchange bias (EB) has received much attention because of its abundant applications in magneto-electronic devices. In the EB effect, induced by the magnetic coupling at ferromagnet (FM)-antiferromagnet (AFM) interfaces, the center of the hysteresis loop is shifted along the magnetic field axis by an amount of the exchange field $H_E$ [1, 2, 3]. 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 studied extensively [4], in which $H_E$ and $H_C$ are often found to decrease gradually while cycling the system through successive hysteresis loops. In most studies on the training effect of either type I or type II [5], the coercive field of the descent branch is shifted greatly while that of the ascent branch does not change much [6], and $H_E$ and $H_C$ can generally be fitted by a linear function of $1/\sqrt{n}$ [7]. Moreover, most of studies have focused on the training effect of the in-plane EB. In contrast, the training effect of the perpendicular EB has been less well understood [8]. To elucidate the EB training effect, various theoretical models have been proposed [8, 9]. In these models, effects of temperature and AFM layer thickness $t_{AFM}$ on the EB training effect are considered. Up to date, however, the effect of the magnetization reversal mechanism on the training effect has been neglected. In this Letter, we have studied the training effect of the perpendicular EB in Pt/Co/Pt/IrMn multilayers, in which the magnetization reversal process of either branch is accompanied by domain wall motion. Although $H_E$ shows a prominent training effect, $H_C$ almost does not change with cycling number $n$. This new feature clearly indicates that the EB training is strongly related to the magnetization reversal mechanism.

A large specimen of Pt(3 nm)/Co(0.5 nm)/Pt(0.5 nm)/IrMn(4 nm) was also grown. The base pressure of the system is $3.2 \times 10^{-5}$ 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. $m_x$ and $m_y$ signals were recorded simultaneously by vector vibrating sample magnetometer (VVSM) of model 7407 from LakeShore Company. All measurements were performed at room temperature.

Figure 1 demonstrates typical out-of-plane hysteresis loops of a uniform sample Pt(3 nm)/Co(0.5 nm)/Pt(0.5 nm)/IrMn(4 nm) with $n=1, 2,$ and 30. Apparently, the perpendicular EB is well established. $H_E$ and $H_C$ are 289/265, 257/254, and 131/247 in the unit of osterds for $n=1, 2,$ and 30, respectively. Two distinguished characteristics can be found. At first, $H_E$ decreases with $n$ but $H_C$ does not change much. During subsequent measurements, both the coercive field of the descent branch and that of the ascent branch move towards the positive magnetic fields [5, 6]. Remarkably, the amount of the field shift for the ascent branch is almost equal to that of the descent branch, unlike conventional results in which the amount of the field shift for the ascent branch is much smaller than that of the descent branch. Secondly, for the present Pt/Co/Pt/IrMn multilayers, the asymmetry of hysteresis loop is equal to zero and does not change during subsequent measurements, as revealed by the curve of $m_y - H$. It is quite different from the conventional results in which the asymmetry changes greatly after the first magnetization reversal [8].

Figure 2 shows the dependence of $H_E$ and $H_C$ on $n$. $H_E$ decreases gradually with increasing $n$. $H_E(n=30)$ is reduced to be less than half of $H_E(1)$. For comparison, it is fitted by a linear function of both $1/\sqrt{n}$ and $e^{-n}$. One can find that the exponential function can better fit the measured results, except for $n=1$. More remarkably, $H_C$ does not change for $n > 2$, except for the first drop, which has been explained as a result of the spin flop in the AFM layer [8].
At first, it should be pointed out that the new feature of the training effect is not intrinsic properties of the perpendicular EB. This is because in perpendicularly exchange-biased Co/Pt/CoO multilayers, $H_C$ is also found to shrink during subsequent measurements of hysteresis loops [1]. As analyzed above, salient phenomena are induced by the unique magnetization reversal mechanism. As shown in Fig. 1 the magnetization reversal process for either the descent branch or the ascent one is accompanied by the domain wall motion because there is no magnetic component perpendicular to the external magnetic field. This can also be convinced by the curve of $H_C$ versus the orientation of the external magnetic field $\theta_H$ as shown in Figure 3. $H_C$ initially increases as the external magnetic field is deviated from the normal direction and then decreases sharply, which can be fitted by the modified Kondorsky model [10]. A maximal $H_C$ is located at the critical angle $\theta_{HC}$ of 60 degrees, which is determined by the competition between the pinning field of domain wall and the uniaxial anisotropic field. Similar results were obtained in other films [11, 12, 13] and attributed to the hindered domain wall motion. As the pinning field is smaller than the uniaxial anisotropic field at $\theta_H$ smaller than $\theta_{HC}$, the magnetization reversal process is accompanied by the pinned domain wall motion and $H_C(\theta_H) \propto H_C(0)/\cos(\theta_H)$, in which $H_C(0)$ refers to the coercivity at the direction normal to the film plane. As the pinning field is larger than the uniaxial anisotropic field at $\theta_H$ larger than $\theta_{HC}$, the coherent magnetization rotation occurs and the coercivity decreases with increasing $\theta_H$. In experiments, we found that for Co/Pt multilayers, the magnetization reversal process is also accompanied by the domain wall motion. Therefore, Pt/Co/Pt and Pt/Co/Pt/IrMn multilayers have the same magnetization reversal mechanism.

With exchange coupling at the FM/AFM interface, the AFM spins are dragged by the exchange field from the FM layer. With pinned domain wall motion, the FM magnetization and thus the exchange field exerted on the AFM spins are either parallel or antiparallel to the pinning direction during measurements of hysteresis loop. Accordingly, the AFM spins can only be switched by 180 degrees [14] and the number of the AFM spins parallel to the pinning direction is changed, leading to the training effect of $H_E$. For the present FM/AFM multilayers, the coercive field at $\theta_H = 0$ for the ascent (+) and the descent (-) branches are equal to the effective pinning fields, i.e. $H_C(\pm) = -H_E \pm \frac{1}{M_{Fm}} (\partial \gamma / \partial x)_{\text{max}}$, where the domain wall energy $\gamma$ consists of two parts, including the domain wall energy of the FM layer and the interface energy. The former one corresponds to the intrinsic coercivity of the FM layer and the latter one to the coercivity enhancement. Apparently, the inhomogeneity of the latter one does not change during the sweeping of the magnetic field. It is different from the case of the magnetization coherent rotation during the magnetization reversal process, in which the coercivity enhancement is contributed from the effective uniaxial anisotropy induced by rotatable AFM grains [15]. During the sweeping of the magnetic field, the switching of AFM grains is triggered from the non-equilibrium orientation to equilibrium one. Less AFM grains can be rotated after subsequent measurements and the coercivity is reduced.

Figure 4 shows the dependence of $H_{E/C}(n = 1)$ and the training effect on $t_{AFM}$. At $t_{AFM}$ smaller than 3.6 nm, $H_{E/C}(n = 1)$ is equal to zero. With increasing $t_{AFM}$, it increases sharply and finally approaches saturation. Meanwhile, $H_C$ acquires a maximum at $t_{AFM} = 4.5$ nm. As $t_{AFM}$ is increased, $\Delta H/E/H_{E}(1)$ inclines to the maximum sharply and then decreases dramatically whereas $\Delta H_C/H_{C}(1)$ is negligible for all $t_{AFM}$. These results can be understood using a simplified thermal activation model [15]. At small $t_{AFM}$, the energy barrier (the product of the volume and the anisotropy energy) is too small to overcome the thermal energy and thus all AFM grains are in the superparamagnetic state, resulting in zero $H_E$ and small $H_C$ and negligible training effect. At the intermediate $t_{AFM}$, some AFM grains become thermally stable, which results in non-zero $H_E$, the $H_C$ enhancement, 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 training effect of $H_E$ is suppressed.

In summary, the Pt/Co/Pt/IrMn multilayers were fabricated and the perpendicular EB is established. For both single FM and FM/AFM multilayers, the magnetization reversal is accompanied by the domain wall motion. The asymmetry of hysteresis loop is always equal to zero during subsequent measurements. The exchange field decreases greatly as an exponential function of $n$ while the coercivity does not change. It is clearly demonstrated that the EB training effect strongly depends on the magnetization reversal mechanism of the FM layer.

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FIG. 1: Figure 1 Typical out-of-plane hysteresis loops of Pt/Co/Pt/IrMn multilayers for $n=1$ (a), 2 (b), and 30 (c).

FIG. 2: Figure 2 Dependence of $H_E$ (solid square) and $H_C$ (solid circles) on $n$ under the external magnetic field along the film normal direction. The solid and dot lines refer to the fitted results of the exponential function and the power function, respectively.

FIG. 3: Figure 3 Dependence of measured $H_C$ (solid square) on the orientation of the external magnetic field. Here, the solid line refers to $H_C(\theta_H) \propto H_C(0)/\cos(\theta_H)$.

FIG. 4: Figure 4 Variations of $H_E$ (solid square) and $H_C$ (solid circles) (a), $\Delta H_E/H_E(1)$ (solid square) and $\Delta H_C/H_C(1)$ (solid circles) with $t_{AFM}$ (b)

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