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# Spin-transfer effect and independence of coercivity and exchange bias in a layered ferromagnet/antiferromagnet system

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The correlation between coercivity and exchange-field shift in a ferromagnetic/antiferromagnetic system has been investigated. By applying a spin-polarized current pulse with an external magnetic field, the exchange-field shift can be changed. Since the different magnitude of exchange fields were achieved on one sample, the coercivity and exchange-field shift can be studied without varying the structure or morphology of the film. Studies were also extended to measurements on spin valves with variable normal-metal thicknesses. Experimental results showed that the spin-polarized current applied in the film plane effectively changes the exchange-field shift while the coercivity remains the same. The results provide convincing evidence for the absence of a direct correlation between increased coercivity and exchange-field shift.

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Exchange bias (EB), which has been known for more than 50 years, refers to the exchange interactions at an interface between a ferromagnetic (FM) and an antiferromagnetic (AF) material.[1,2] The EB effect has potential application in magnetoresistive sensors, magnetic random access memory, and for surpassing the superparamagnetic limit in magnetic nanoparticles.[3–5] In studying EB, many groups have found that the exchange-field shift $H_{ex}$ is inversely proportional to the thickness ($t_{FM}$) of the FM layer, which is pinned by the AF layer, and the coercivity ($H_c$) of the pinned FM layer is increased with $H_{ex}$ (Refs. 6–9). Some researchers have come to the conclusion that both the increase in $H_{ex}$ and coercivity are the results of the interfacial exchange coupling between the AF and FM layers, and predicted that $H_c$ should depend on $1/t_{FM}$ or $(1/t_{FM})^{3/2}$.[10,11] However, other researchers have reached completely opposite conclusions. The increase in $H_c$ and $H_{ex}$ are not directly related with each other in the sense that $H_c$ can be varied without changing $H_{ex}$ and vice versa.[12,13]

Fundamentally, exchange coupling is an interfacial phenomenon while coercivity is known to be significantly affected by the microstructure of the films. In order to study exchange-field shift and coercivity simultaneously, avoiding variations in sample preparation, wedged samples or films with the same crystallographic structure have been used in the experiments.[10,14] However, these approaches do not ensure samples have been fabricated without variation in the structure or morphology of the film.

Recently, both experiments and theoretical analyses have provided evidence that a polarized current can change the strength and direction of the exchange-field shift in a spin valve (SV) based on a spin-transfer (ST) effect.[15–19] The current-perpendicular-to-plane (CPP) geometry and the current-in-plane (CIP) geometry were involved. Furthermore, spatially nonuniform modes of reversal by ST has also been observed in an AF oxide layer coupled to a nanomagnet.[20] In general, ST between the FM layers in a SV or magnetic tunneling junction structure is expected in CPP geometry. This also applies to AF spin torque. However, the moments at the FM/AF interface, which are shown in Fig. 1, are gradually orientated parallel to the FM according to many models and experiments.[21–23] Thus, spin-polarized electrons flowing from an FM into an AF at the FM/AF interface are not parallel to the AF moments whenever CPP or CIP geometry is used. Viewing the geometry of the CIP-SV in Fig. 1, there are three FMs: the free layer, the pinned layer, and the uncompensated spin at the FM/AF interface. When a pulse applied with a large magnetic field, the magnetic moments of the free and pinned layers were parallel. Hence, the spin-polarized pulse cannot transfer angular momentum between them. However, the orientation of polarized electrons flowing from the pinned layer to the AF is parallel to the moment of pinned layer and not parallel to the moments at the FM/AF interface. Therefore, in the spin valve of CIP geometry, only the polarized electrons flowing from the FM to AF layer can transfer spin angular momentum and affect the micromagnetic state distribution of the FM/AF interface. During the measurements, if the external magnetic field applied with the pulse is antiparallel to the exchange-field direction, the ST tends to rotate and finally reverse the moments at the FM/AF interface.[18,19] Since the strength of $H_{ex}$ is strongly correlated with the micromagnetic state distribution of the FM/AF interfacial layer, based on ST, different $H_{ex}$ can be achieved in the same sample by applying polarized current pulses of different magnitude.[24–26]

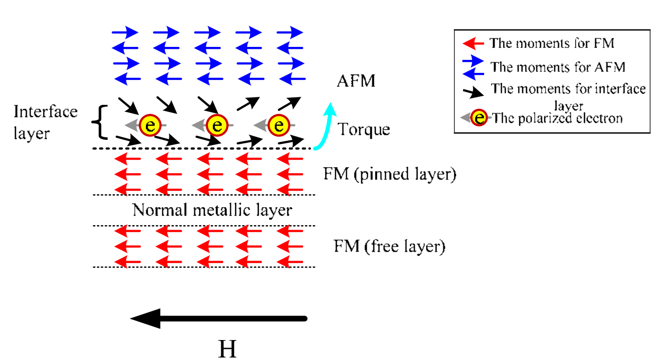



FIG. 1. (Color online) Schematic illustrations of the influence of transport currents on exchange-bias effect in a CIP-spin valve.

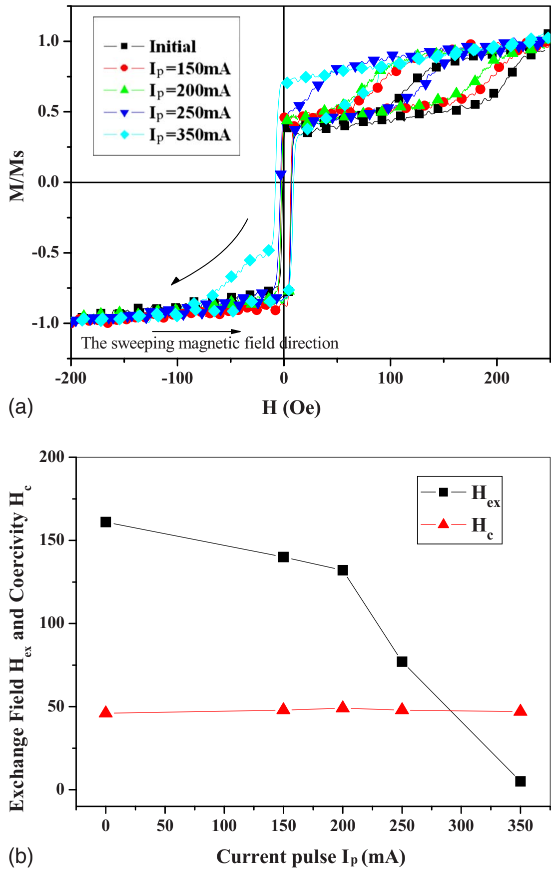



FIG. 2. (Color online) Different $I_p$ pulses applied to Ta (10 nm)/NiFe (12 nm)/Cu (4 nm)/NiFe (4 nm)/FeMn (15 nm)/Ta (5 nm) to set the exchange-field shift: (a) the magnetization hysteresis curves for various values of $I_p$, and (b) exchange-field shift and coercivity variations versus $I_p$.

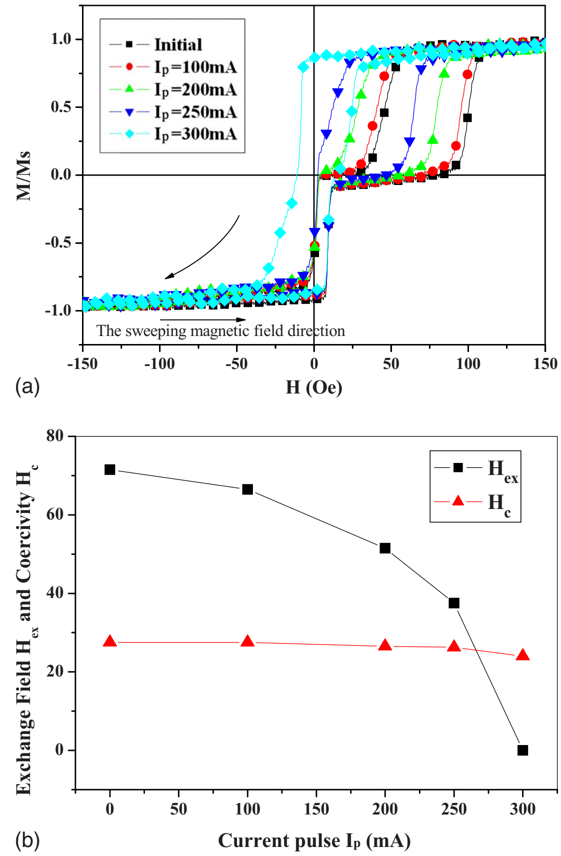



FIG. 3. (Color online) Different $I_p$ pulses applied to Ta (10 nm)/NiFe (12 nm)/Cu (4 nm)/NiFe (12 nm)/FeMn (15 nm)/Ta (5 nm) to set the exchange field: (a) the magnetization hysteresis curves for various values of $I_p$, and (b) exchange field shift and coercivity variations versus $I_p$.

Hence, this effect provides a way of simultaneously studying the changes in exchange field shift and coercivity within a single sample of the same microstructure. In this Brief Report, we report studies of the exchange field shift and coercivity of NiFe/FeMn in an EB-SV. In previous research, it has been observed that the exchange-field shift of NiFe/FeMn exchange-biased system is roughly inversely proportional to the thickness of the NiFe-pinned layer. However, the relation between the thickness of NiFe-pinned layer and coercivity has no confirmed conclusion because the coercivity is affected by the microstructure of the pinned layer, which inevitably changes from system to system.[6] By studying the exchange field with polarized currents of different magnitude, we have obtained experimental evidence that the exchange-field shift changes without a variation in the coercivity. The increased $H_c$ and $H_{ex}$ have no direct correlations. Samples of Ta/NiFe/Cu/NiFe/FeMn/Ta were grown in a dc magnetron sputtering system on a $5\times5$ mm$^2$ Si substrate with a constant magnetic field of $\sim300$ Oe applied along the substrate to develop the exchange field. Full details of the preparation process have been given in a previous publication.[25] The $H_{ex}$ and $H_c$ were determined from the magnetization hysteresis loops measured by a BHV-525 vibrating sample magnetometer (VSM) at room temperature.

To study the exchange field with polarized pulses of different magnitude, the samples Ta (10 nm)/NiFe (12 nm)/Cu (4 nm)/NiFe($x$ nm)/FeMn (15 nm)/Ta (5 nm) were fabricated. We set $x=4$ nm in sample I and 12 nm in sample II to achieve relative large and small $H_{ex}$. The measurements were carried out as follows. First, a pulse current of 150 mA with a 100 ms duration was applied to the top of the sample plane from two probes. The distance between the probes is 3.5 mm. The current density is only $\sim10^5$ A/cm$^2$ by assuming that the current flows homogeneously in the layer. Simultaneously, a 1.5 kOe external field $H_p$ was applied antiparallel to the exchange-field direction. This large external field was used to suppress the current-induced reversal of the pinned NiFe layer and to maintain its magnetic moments along the external field direction. Then, after the given pulse was applied, the magnetization hysteresis ($M$-$H$) loops along the exchange-field direction were measured immediately by VSM. Finally, a pulse of the same magnitude was applied with the $H_p$ direction reversed. This step can set the $H_{ex}$ to its initial magnitude.[27] The process was repeated for pulses $I_p$ of 200, 250, and 350 mA for sample I and 200, 250, and 300 mA for sample II. Figure 2(a) shows the variations in the $M$-$H$ curves for sample I after each pulse $I_p$ was applied. The form of the $M$-$H$ curves is typical for SV. Starting from negative field, $M/Ms$ ($M$: magnetization and $Ms$: saturated magnetization) is at a negative maximum value. It indicates

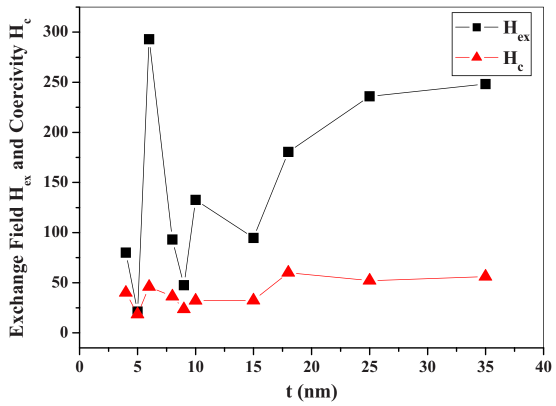
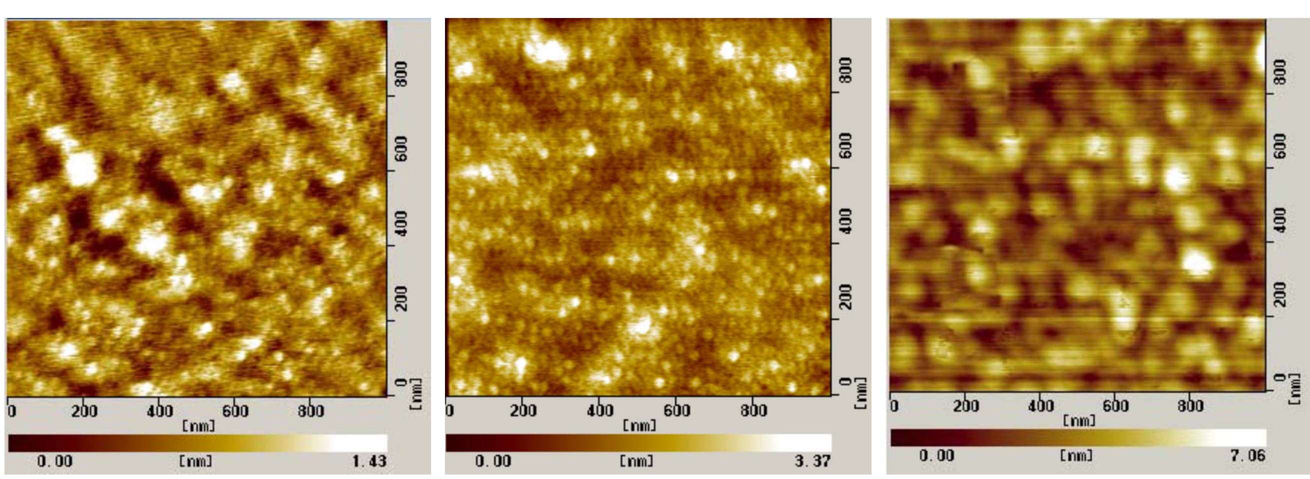



FIG. 4. (Color online) Exchange-field shift and coercivity variations in the Cu space thickness $t$ in the pinned system.

that the magnetizations of the two NiFe layers are parallel. Close to zero field, the magnetization of the free NiFe layer switches, leading to an antiparallel alignment of the two NiFe layers. Then, at a higher positive field (designated as $H_1$) beyond the $H_{ex}$, the magnetization of the pinned NiFe layer is finally reversed. On sweeping back, at the field (designated as $H_2$) lower than the $H_{ex}$, the pinned layer switches back and around zero field the free layer switches. Then, $H_c$ for pinned layer is clearly defined as $H_c=(H_1\text{-}H_2)/2$, and the shift of the center of the minor $M$-$H$ loop from the zero field is referred to as the $H_{ex}$. As can be seen in Fig. 2(b), $H_c$ remains unchanged and $H_{ex}$ changes a lot with increase the magnitude of the pulse. For the sample II with relative small $H_{ex}$, we have repeated the measurements as sample I. The results shown in Fig. 3 also indicated that $H_c$ keeps as a constant with decrease the $H_{ex}$. In changing $H_{ex}$, Joule heating may play a major role according to previous research.[28,29] A detailed study of the impact of Joule heating in the same sample system has been researched.[30] The observations suggest that Joule heating plays a minor role in our measurements, thus providing more convincing evidence of the spin torque exerted on the interfacial antiferromagnetic moments to change the exchange field. Since different values of $H_{ex}$ were achieved in one sample and the polarized pulse magnitude only affects the distribution of AF moments according to the illustration in Fig. 1, the unchanged $H_c$ provides evidence that the exchange interaction between the AF and FM moments has no influence on the coercivity. There is no direct correlation between the coercivity and exchange-field shift. These results are opposite to those of some previous reports[10,11] since the samples using in their studies may have different morphologies.

The properties of exchange bias are relative not only to the pinned layer but also to the film under the pinned layer.[31] Therefore, another experiment was performed. A series of EB-SV samples with structure Ta (10 nm)/NiFe (12 nm)/Cu($t$ nm)/NiFe (8 nm)/FeMn (15 nm)/Ta (5 nm) were fabricated. The pinned-layer thickness was fixed and that of the normal metallic layer Cu was varied over a wide range ($t$=4–35 nm). $H_{ex}$ and $H_c$ for the pinned systems, as determined from $M$-$H$ loops, are shown in Fig. 4. It can clearly be seen that $H_{ex}$ varied over a wide range (about 30–300 Oe) on increasing the thickness of the Cu layer. However, $H_c$ remains within a narrow range of values and does not increase with $H_{ex}$. During the fabrication process of the SV samples, multilayer systems composed of Ta (10 nm)/NiFe (12 nm)/Cu($t$ nm)/NiFe (8 nm) without the AF layer were also deposited at the same time. The surface morphologies for the samples with $t$=4, 6, and 25 nm, which have almost the same magnitude of $H_c$ and different $H_{ex}$, were characterized by means of atomic force microscopy (AFM, Seiko SPA-300HV).

An AFM image of an 8-nm NiFe film on a 4-nm Cu layer in Fig. 5(a) showed the film to have a very smooth surface morphology with a root-mean-square roughness ($R_{rms}$) of only 0.297 nm. On increasing the thickness of Cu layer to 6 nm, the top NiFe film also had a very smooth surface morphology ($R_{rms}$=0.459 nm) but a large number of small is-




(a) (b) (c)

FIG. 5. (Color online) AFM images of NiFe (8 nm) thin films on (a) Cu (4 nm), (b) Cu (6 nm), and (c) Cu (25 nm) in Ta (10 nm)/NiFe (12 nm)/Cu($t$ nm)/NiFe (8 nm) multilayer.

lands emerged, as shown in Fig. 5(b). When the thickness of the Cu layer was increased to 25 nm, these small islands were enlarged and the value of $R_{rms}$ increased to 1.21 nm. As shown in Fig. 4, $H_{ex}$ for the SV samples with the three different thicknesses of Cu layer were 80, 294, and 236 Oe, respectively. However, their $H_c$ values were 40, 46, and 52 Oe, respectively, which are not increased with $H_{ex}$. Since the pinned-layer thickness is the same and only the thickness of the Cu layer is changed, taken together with the AFM analyses, the results indicated that the surface morphology of the pinned NiFe layer has the greater influence on $H_{ex}$ than on $H_c$. Therefore, we have not observed that $H_c$ increased in the same way as $H_{ex}$.

In conclusion, based on the change in the distribution of AF moments by the ST effect, we have studied the relationship between the coercivity and exchange-field shift in an FM/AF system. Our results suggest that the coercivity is not changed in the presented ST experiments but the exchange-field shift can be changed independently. The observations provide compelling evidence that the appearance of increasing exchange-field shift and coercivity in an EB system have no direct correlation, which has been debated in previous research publications. Furthermore, $H_c$ can be varied without changing $H_{ex}$ and vice versa.

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