Changing Exchange Bias in Spin Valves with an Electric Current

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We show that a high-density electric current, injected from a point contact into an exchange-biased spin valve, systematically changes the exchange bias. The bias can either increase or decrease depending upon the current direction. This observation is not readily explained by the well-known spin-transfer torque effect in ferromagnetic metal circuits, but could be evidence for the recently predicted current-induced torques in antiferromagnetic metals.

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An electrical current can transfer spin angular momentum to a ferromagnet [1–6]. This novel physical phenomenon, called spin transfer or spin torque, offers unprecedented spatial and temporal control over the magnetic state of a ferromagnet and has tremendous potential in a broad range of technologies, including magnetic memory and recording. It was recently predicted [7] that current-induced torques are a general property of magnetic metals not limited to ferromagnets (FM) and, in particular, that spin torques act on the order parameter of antiferromagnetic (AFM) circuit elements. Unlike spin torques in a FM metal, which follow from conservation of total spin and act only near interfaces, current-induced torques in AFM metals are not related to total spin conservation and have a bulk contribution [7].

In this Letter we show that a high-density dc current injected from a point contact into an exchange-biased spin valve (EBSV) [8] can systematically change the exchange bias [9–11], increasing or decreasing it depending upon the current direction. From observations of qualitatively similar behaviors in spin valves (SV) with equal (symmetric SV) and unequal (asymmetric SV) FM-layer thicknesses, we infer that the source of these changes is almost certainly not the usual spin torque exerted by the current on the FM layers. Our data can instead be explained qualitatively in terms of a current-induced torque acting on magnetic moments in the AFM component of SV structure. This new effect could be used to control the magnetic state of spin-valve devices, e.g., in magnetic memory applications.

Because of their exceptional responsiveness to magnetic fields, EBSVs are chosen for devices such as magnetic field sensors, read heads in hard drives, and galvanic isolators. Our EBSVs consist of two Co(9%Fe) FM layers separated by a nonmagnetic (N) Cu-spacer thick enough that exchange coupling between the FM layers should be small. The magnetization direction of one FM layer is "pinned" in a fixed direction by the presence of an adjacent FeMn AFM layer [9–11], while the magnetization direction of the other FM layer is free to switch from parallel (P) to antiparallel (AP) to that of the first layer. Such spin valves exhibit giant magnetoresistance [12]; i.e., the SV resistance is smallest for P alignment of the two magnetizations and largest for AP alignment. Switching from P to AP is achieved by applying an external magnetic field in the plane of the layers.

To generate a high-density electrical current, we use point contacts. Point contacts were instrumental both for the original observation of spin transfer in ferromagnetic materials [3] and in probing high-frequency manifestations of this phenomenon [13–15]. The extremely small size, less than a trillionth of a square cm, qualifies point contacts as the smallest probes of spin transfer phenomena, enabling current densities up to 10^{13} A/m^2. Our point contacts were made with a standard system [3,16], using a sharpened Cu wire and a differential screw mechanism to move the Cu tip toward a FeMn/CoFe/Cu/CoFe EBSV. The spin-valve structures were sputtered onto Si substrates using techniques described previously [17], and had a 5 nm thick Au protective cap and a thick (50 or 100 nm) Cu underlayer. The latter was used to secure a closely perpendicular-to-plane flow of the current (CPP) from the point contact, across the spin valve, and into the Cu buffer. Three standard SVs: (I) FeMn(8 nm)/CoFe(3 nm)/Cu(10 nm)/CoFe(10 nm), (II) FeMn(3 nm)/CoFe(3 nm)/Cu(10 nm)/CoFe(10 nm), (III) FeMn(8 nm)/CoFe(3 nm)/Cu(10 nm)/CoFe(3 nm) and two inverted SV structures: (IV) CoFe(10 nm)/Cu(10 nm)/CoFe(3 nm)/FeMn(8 nm), (V) CoFe(3 nm)/Cu(10 nm)/CoFe(3 nm)/FeMn(8 nm) were studied. SVs (I), (II), and (IV) are asymmetric, and SVs (III) and (V) are symmetric. The samples were cooled through the Néel temperature of FeMn ($T_N \approx 400$ K) in the presence of a static magnetic field (~18 mT) and zero applied current, to pin the magnetization direction of the neighboring CoFe. A total of 29 point contacts with resistances from 0.7–5 Ω showed the characteristic behaviors that we describe with the help of representative data from a 0.92 Ω contact to sample (I), a 2.72 Ω contact to sample (III), and a 1.59 Ω contact to sample (IV).

At room temperature and in magnetic fields B up to 0.1 T applied along the exchange-bias direction, we have measured the magnetoresistance (MR) of point contacts at different bias currents. Figure 1 shows typical variations in the contact resistance $R = V/I$ as a function of the applied field B (solid traces) for a series of bias currents I. Black (gray) traces show sweeps from high positive (negative) field to high negative (positive) fields. Here negative current corresponds to the flow of electrons from the tip into the spin valve. For a given bias current I (given trace in Fig. 1) the form of $R(B)$ is typical for spin valves: starting from high positive field, $R(B)$ is constant at a minimum value (magnetizations of the two CoFe layers are parallel), rises to a maximum when the magnetization of top (free) CoFe layer switches near zero field (leading to antiparallel alignment of the two CoFe layers), and then decreases to its minimum value beyond the exchange-bias field at which the magnetization of the pinned CoFe is finally reversed. The reversed sweeps from high negative to high positive fields show similar behavior. The reversal of both free and pinned CoFe layers and the corresponding variations in R proceed via a discrete series of irreversible steps. The latter correspond to reversals of individual ferromagnetic domains in CoFe probed by the point contact. Note that domains closest to the contact contribute most to its resistance. No reversible steps in contact resistance, which correspond to dynamic excitations [3] in FM layers, were observed in these measurements.

The reversal of the free layer seems to be little affected by the applied current. In contrast, the current both broadens the reversal transition of the pinned layer, and clearly changes the average exchange-bias field. The changes in the exchange bias are reversible when current is stepped up or down and exhibit no significant ''training'' effects. The 2D gray-scale plot representation [see Fig. 2(a); lighter color indicates higher resistance] of the data in Fig. 1 suggest that on average the exchange bias increases with applied negative current and decreases with positive one. The white dashed, white solid, and black-dashed lines in Fig. 2 are the least-squares linear fits to the $R(B)$ data points at the 30%, 50%, and 70% levels, respectively, assuming 0% for minimum resistance (P state) and 100% for maximum resistance (AP state). The resulting slopes of 0.23 (30%), 0.26 (50%), and 0.2 (70%) T/A in Fig. 2(a) emphasize the overall trend, and also highlight stochastic variations that occur on top of this trend. Although the resistance curve near switching varies from run-to-run at a given current, the trend indicated by the white fits is always present. For comparison, Figs. 2(b) and 2(c) show exchange-bias variations in an inverted structure IV where the FeMn pinning AFM lies on top of the SV stack, and in a symmetric structure III where the pinned and free FM layers have the same thickness. While the symmetric SV of 2(c) exhibit qualitatively similar variations in exchange bias to 2(a), the response of the inverted structure 2(b) is different. Here positive current crosses the FeMn/CoFe interface in the opposite sense compared to 2(a) (i.e., from FeMn into CoFe), and the effect of the current on the exchange bias is reversed [slopes = −0.20 (30%), −0.02 (50%), and −0.01 (70%) T/A]. Note that the observed asymmetry of the current-induced variations in exchange bias cannot be explained by heating effects, which are symmetric in current.

A conventional spin-transfer torque explanation of our data can be attempted by viewing the system as being

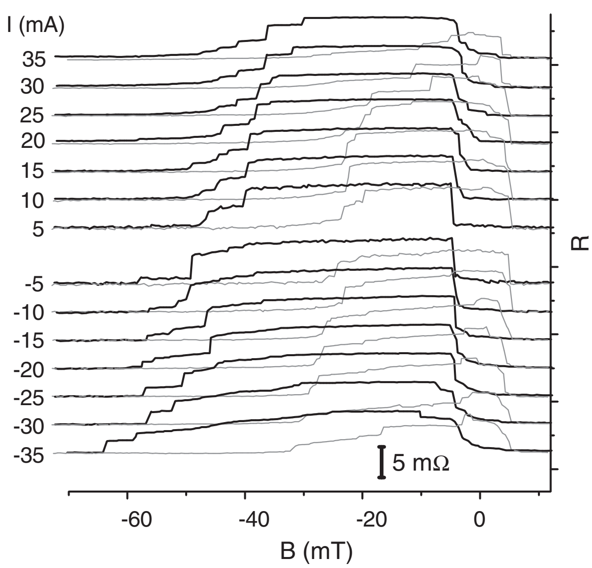

FIG. 1. Point-contact magnetoresistance at different bias currents. Solid traces show point-contact resistance $R = V/I$ as a function of the applied magnetic field B for a series of bias currents I (− 35, −30, −25, −20, −15, −10, −5, 5, 10, 15, 20, 25, 30, 35 mA). Black (gray) traces are for B sweeps down (up). The MR sweeps at different currents are shifted along the vertical axis for clarity. The point-contact resistance at high fields is 0.92 Ω.

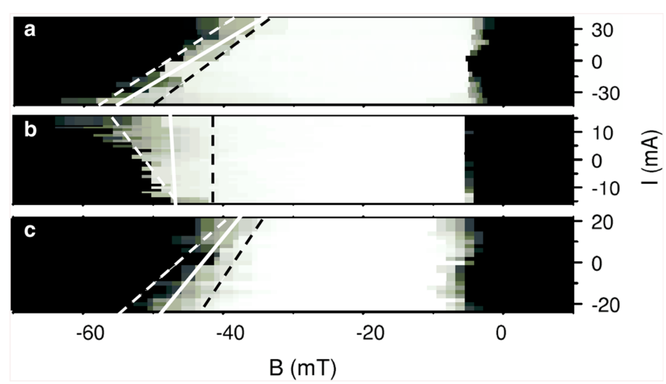

FIG. 2 (color online). Variation of exchange bias in standard and inverted spin-valve structures. 2D gray-scale plots show the point-contact magnetoresistance (down sweeps) as a function of the bias current in (a) standard, (b) inverted, and (c) symmetric spin-valve structures. Lighter color indicates higher resistance with black/white corresponding to (a) 0.919 Ω/0.926 Ω, (b) 1.590 Ω/1.596 Ω, (c) 2.720 Ω/2.733 Ω. In (b) and (c) the current was stepped up from high negative values while in (a) it was stepped down from high positive ones. See text for details.

composed of three ferromagnets; the free ferromagnet, the pinned ferromagnet, and the surface layer of the antiferromagnet which includes uncompensated pinned moments [18,19]. In this picture, spin torques act on the pinned FM layer due to transport electron transmission through or reflection off both the free FM layer and the AFM layer. The spin torque acting on the pinned FM layer due to the free one, is necessarily [20] accompanied by a "reaction" torque acting on the free FM layer due to the pinned one. Indeed, these two torques are expected [20] to have the same magnitude when the pinned and free FM layers have the same thickness. However, as illustrated by the sample III data in Fig. 2(c), the behavior observed in symmetric structures is similar to that of asymmetric ones; the switching field of the free FM layer is essentially unaffected by current in all SV structures over the current range studied here. We argue below that the qualitative difference in the influence of current on the two CoFe layers is due to a large difference in the current-induced torques they experience, a difference that is not allowed by the spin-transfer mechanism applied solely to the FM layers. Some simple mechanisms that could produce a difference can be discounted on experimental grounds. In particular, the difference in damping, which competes with torques in current-induced switching phenomena, would produce an effect opposite to the one we observe because the pinned layer is more strongly damped [21] than the free one. Spin-transfer torques between the pinned magnet and uncompensated pinned spins in the antiferromagnet cannot be significant because of the orders of magnitude difference in total spin between these ferromagnetic subsystems. Finally, the sign of the observed effect (positive currents promote parallel configuration of the two FM layers) is opposite to what one expects for the usual spin-transfer effect. The above arguments rule out the conventional spin-transfer effect between the two CoFe layers as the explanation of our observations.

A natural explanation of our data is provided by the ideas put forward in Refs. [7,22] in which current-induced torques are calculated microscopically by evaluating spin densities in the nonequilibrium current-carrying state. In this time-dependent mean-field (e.g., time-dependent spin-density functional) based picture, spin torques are due to the contribution of transport electrons near the Fermi energy to the spin-dependent exchange-correlation potential, which is [7] in turn proportional to the corresponding spin-density contribution. Current-induced changes in the exchange-correlation effective magnetic field are experienced by all magnetic atoms and are generically nonzero in any circuit with noncollinear moments whether arranged ferromagnetically, antiferromagnetically, or in some more complex spatial arrangement. Conservation of total spin, which is relevant for order parameter dynamics in a ferromagnet, but not in an antiferromagnet, is not a necessary condition for current-induced spin torques. It does, however, simplify its description in a system composed of coherent ferromagnetic elements to the commonly used action-reaction picture, with separate current-carrying quasiparticle and collective magnetization degrees of freedom.

From Refs [7,22] it follows on quite general grounds that the moment arrangement near the FM/AFM interface is altered by a transport current. Since the moment arrangement near this interface is complex and still not fully characterized even in the absence of a current, we are able at present to provide only the qualitative explanation for the dependence of exchange bias on transport current summarized schematically in Fig. 3. Near the exchange-bias field, the metastability of the ferromagnet's opposite to field orientation is due almost entirely to exchange interactions with uncompensated moments in the surface layer of the antiferromagnet. Some of these spins are pinned, thereby inducing an energy barrier for ferromagnetic layer spin reversal [18,19]. Electrons flowing from the ferromagnet into the antiferromagnet [7] induce torques on mo-

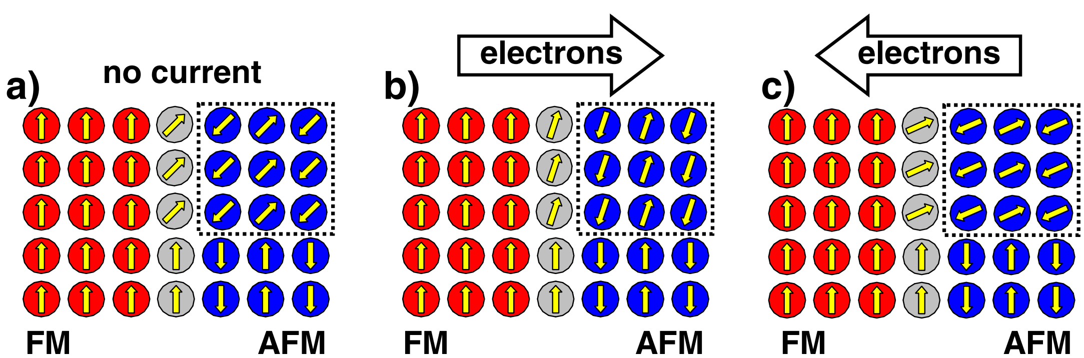

FIG. 3 (color online). Schematic illustration of the influence of transport currents on exchange bias. (a) The surface layer of an antiferromagnet contains uncompensated magnetic moments (gray). A fraction of the uncompensated moments are pinned. They do not reverse when the adjacent ferromagnet reverses and are responsible for the existence of exchange bias. The dotted line indicates an antiferromagnetic domain. (b)-(c) Exchange bias will increase (decrease) if the configuration of pinned moments is altered to increase (decrease) the total component along the exchange-bias direction. The pinned moments are exchange coupled to the bulk antiferromagnet and will be reoriented by torques that act in the bulk of the antitferromagnet.

ments in the antiferromagetic matrix, which alter its magnetic configuration. These torques tend to favor parallel alignment of moments at the ferromagnet/antiferromagnet interface [7] and will therefore tend to increase the exchange-bias field. Electrons flowing in the opposite direction will tend to have the opposite effect.

Our simple picture does not attempt to account in detail for the domain structure and disorder in both materials near the FeMn/CoFe interface that is presumably responsible for stochastic run-to-run variations, but we believe that it gives the correct qualitative explanation for the overarching trend identified in our data. The experiment admittedly does not directly imply that the effect we have discovered is due to torques acting on the bulk FeMn antiferromagnet because it does not distinguish torques applied directly to the uncompensated pinned moments from torques applied to buried moments which are exchange coupled to the surface. It nonetheless conclusively demonstrates that the scope of fundamentally interesting and potentially useful current-induced torque phenomena in noncollinear magnetic systems is even broader than the rich variety of ferromagnetic nanomagnet effects explored to date.

Because there is no spacer separating the adjacent FM and AFM layers, strong interactions across the interface imply that changes in the magnetic microstructure of the antiferromagnet will not normally be permanent, but will relax once the current is turned off. Our results suggest though, that it is possible in principle to drive irreversible changes in the antiferromagnet's microstructure with a transport current, and thereby achieve post-growth changes in exchange bias characteristics. The latter supports the feasibility of a programmable magnetic memory element.

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