Current-Driven Switching in a Single Exchange-Biased Ferromagnetic Layer

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We demonstrate spin-transfer torque effects in a single exchange-biased ferromagnetic layer. A current through a point contact to the exchange-biased Co layer reverses the magnetization of a nanodomain in the layer hysteretically for low applied magnetic fields and reversibly for high fields (up to 9 T). These effects are the inverse of the domain wall magnetoresistance, in the same way that similar effects in multilayers are the inverse of giant magnetoresistance.

The recent discovery of spin-transfer torque (STT) effects [1–13] has attracted a great deal of attention due to the novel physics and potential device applications. The STT effects stem from the fact that the spin angular momentum of the electrons carried by a sufficiently large current can align and reverse magnetization of a ferromagnet, a feat previously achieved only by a magnetic field. To date, theoretical and experimental studies of STT effects have been explored in multilayers. In a multilayer, the magnetic configuration of the layers affects its resistance through the giant magnetoresistance (GMR) effect. The STT effect is the inverse effect, where an electrical current alters the magnetic configuration of the constituent layers.

Magnetization reversal in low magnetic fields has been observed in Co/Cu/Co trilayers [5–9], in which the roles of the constituent layers are physically defined. The thicker Co layer serves as the "fixed layer," whereas the thinner Co layer is the "free layer." The current through each layer is preferentially carried by the majority electrons leading to a spin polarized current. The spin polarized current exerts torques on the layers whenever the magnetizations of the layers are not collinear. Depending on the polarity of the current injected perpendicularly through the trilayer, the free layer can be switched between parallel or antiparallel alignments relative to the fixed layer, resulting in a hysteretic dependence of resistance on current via the GMR effect. In high magnetic fields, the observation of a peak in the differential resistance for only one current polarity in Co/Cu/Co trilayers and Co/Cu multilayers has been generally regarded as a sign of spin precession [4–6]. Recent work shows that they are related to precession, but the relationship is complicated [11,14,15].

Although the STT effect in trilayers with GMR is well established, there is still no definitive interpretation of the STT effect in a single ferromagnetic layer without GMR. Myers *et al.* [5] first observed such an effect, but did not pursue it. Ji *et al.* [10] observed peaks in the differential resistance (dV/dI) under a large magnetic field ($2\ \mathrm{T} \leq \mu_0 H \leq 9\ \mathrm{T}$) applied perpendicularly to a Co film. Guided by the prevailing interpretation of experiments [4–6], such signatures in both single and multilayers were interpreted as spin wave excitations. Several calculations [16,17] have shown that there is a precessional instability in single films. In these calculations, the current in the leads becomes spin polarized because of spin accumulation and then drives the instability. However, these calculations only show that the magnetization can become unstable, but do not show how the system evolves or what gives rise to the change in resistance.

In this work, we describe STT effects in a Cu point contact to a single exchange-biased Co layer with a field applied parallel to the film plane. In the film there are three regions: the bulk of the film, which is unaffected by both the current and the exchange bias, the near surface part of the film that is influenced by the exchange bias, but not the current, and a nanodomain beneath the point contact to the Co film. The nanodomain is influenced by current and is coupled to the exchange-biased near surface region. It has two stable magnetization directions relative to the rest of the ferromagnetic (FM) layer. A current injected through the point contact can switch this domain between these two configurations. We show that this STT effect in a single layer evolves from hysteretic switching in low magnetic fields to nonhysteretic switching (differential resistance peaks) in high magnetic fields.

We used a single 400 nm thick Co layer grown by sputtering. A thin antiferromagnetic CoO layer is formed on the top unprotected Co surface by natural oxidation. A large exchange bias field (e.g., -1 T) accompanied by a large coercivity (e.g., 0.5 T) in Co at 4.2 K is known to be induced by very thin CoO layer [18]. The exchange bias allows for bistability between the nanodomain and the rest of the film. To establish exchange bias of the top Co surface, the Co layer was cooled in a magnetic field of $H = +5$ T applied in the film plane from room temperature to 4.2 K and the field was then ramped to zero. The sign of the initial magnetic field establishes the preferential alignment of the top Co surface towards the $+H$

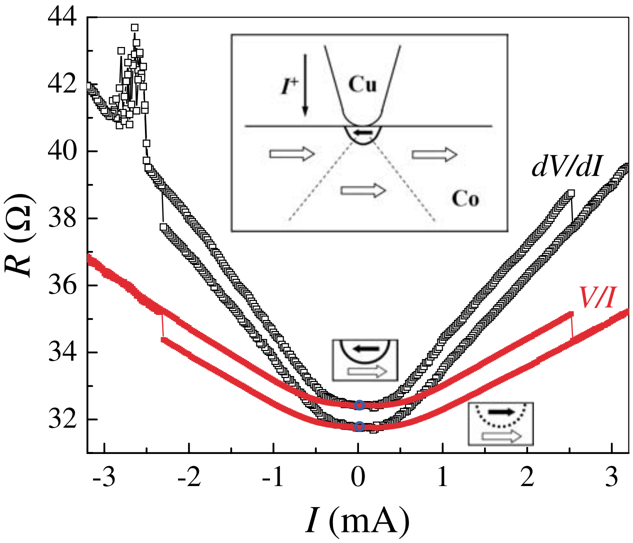

FIG. 1 (color). Hysteretic current-induced switching loop in zero field for a Cu tip in contact with a single Co layer. The model and the spin structures at zero bias are schematically shown in the inset.

direction. The Cu tip, which accommodates a high current density [4,10], was then brought into contact with the Co film as shown in the inset of Fig. 1. Resistance (V/I) and differential resistance (dV/dI) as a function of current (I) were separately measured at the same time at 4.2 K. As shown in Fig. 1, both resistance and differential resistance exhibit a hysteretic switching loop between the low and the high resistance states, very similar to those obtained in Co/Cu/Co trilayers [5,6,9,12]. Positive polarity is defined for current flowing from the tip to the film. As described below, this effect is due to the magnetization reversal of a nanodomain underneath the point contact and above the remaining of FM film (inset of Fig. 1).

To investigate the magnetic configuration in the Co layer, we measured the resistance as a function of the magnetic field applied in the film plane at a small bias current of 0.1 mA, which causes no STT effects. This measurement probes the magnetic state of the nanodomain, but does not directly probe the rest of the near surface region. The results are shown in Fig. 2 for the low field range [(a), ± 0.4 T] and the high field range [(b), ± 0.8 T]. The exchange bias not only causes the nanodomain of the ferromagnet to switch asymmetrically, but it also increases the switching field substantially for both field directions as shown schematically in Fig. 2(c). Thus, for the low field sweeps, the bulk of the film reverses at ± 31.5 mT, but the nanodomain remains intact with the magnetization pointing $+H$.

In the high field range of ± 0.8 T, the exchange bias of the nanodomain will be overcome by some field values. The asymmetrical switching of the top exchange-biased nanodomain and the symmetrical switching of the bottom layer give rise to a very rich field dependence of the resistance as shown Fig. 2(b). At state g, both regions are aligned in the $+H$ direction. In decreasing field, stage g is

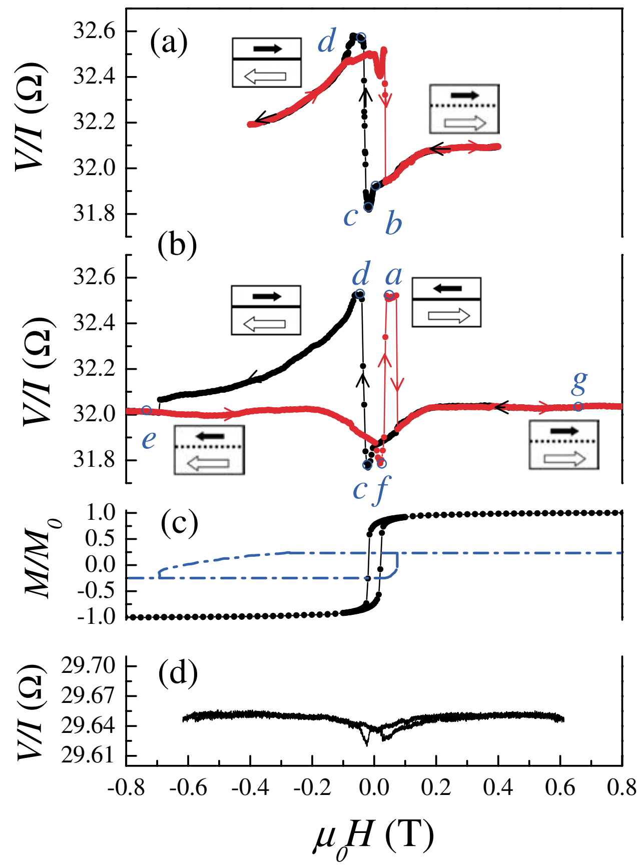

FIG. 2 (color). Magnetoresistance of the contact shown in Fig. 1 with a bias current of 0.1 mA in (a) low field range ± 0.4 T and (b) high field range ± 0.8 T. (d) Magnetoresistance of a 400 nm Co film covered with 4 nm gold with a similar contact resistance. Schematic loops of the bottom (solid curve) and the top (dashed curve) layers are shown in (c).

maintained until the bulk film switches at about -31.5 mT, and the high resistance state d is reached. Further increasing the magnitude of $-H$, the nanodomain magnetization rotates gradually beginning at about -65 mT to -0.695 T before reaching state e with magnetization of both regions in the $-H$ direction. Starting from state e, with increasing field, the low resistance is maintained from -0.8 T to until $+31.5$ mT when the bulk film switches, and the high resistance state a is reached. Further increasing the field to $+72.8$ mT, the nanodomain switches back to $+H$ and the low resistance state g is reached again.

Two effects are expected to give rise to the measured resistance changes, anisotropic magnetoresistance (AMR) and domain wall magnetoresistance (DMR). Reported AMR values for similar films are small ($\triangle R/R = 0.008$) [19]. For the film in Fig. 2, the maximum resistance change for the AMR would be 0.24Ω. This is the same size as the reversible decrease on reducing the field from large positive values, the lower curve in Fig. 2(b), but is significantly smaller than the changes in resistance when the system hysterically switches. In thin films with current in the film plane, the lowest resistance state is when the magnetization is perpendicular to the current flow. In point contact in which current is injected perpendicular to the film, the observed lowest resistance is not at high fields but near the switching field. This may be due in part to the nonuniform current flow in point injection and possibly more complex domain structure. At any rate, the AMR is smaller than the changes observed when switching.

Several crucial aspects should be emphasized. First of all, as shown in Fig. 1, we have accomplished high and low resistance states in a single FM. This new type of STT effect in a single magnetic layer has not been previously reported. The large resistance difference between d and e, and between a and g is due to a domain wall within a single Co layer. The exchange bias on the top surface of the Co layer appears to be essential for the observed STT effects in a single Co layer. We have not been able to observe the STT effect in several Co samples with the top surface protected by an Au layer. As shown in Fig. 2(d), we observe only very small resistance changes, which we attribute to AMR, similar to the reversal part in Fig. 2(a). The asymmetry of Fig. 2(a) and 2(b) reverses when a negative field is used to cool down the single layer.

For the observation of the STT effects in trilayers (e.g., Co/Cu/Co), the reversal of the FM layer is revealed by the GMR effect. In the present case of a single FM layer, there is no GMR. The observed large resistance change is due to the domain wall magnetoresistance (DMR), which comes from spin-dependent scattering of a domain wall separating the nanodomain and the FM layer as shown in the inset of Fig. 1. We note that 25 years ago, Berger predicted that a spin-polarized current can exert a torque on a domain wall, known as the domain drag effect [20]. Our observation is the realization of the STT effect in a single layer due to DMR. While we expect the reversal of the magnetization is due to the pressure on a domain wall exerted by the spin current, nucleation of reversal out of the nominally uniform state could be caused by several effects. Exchange bias can give rise to partial domain walls. Pressure on these partial domain walls may nucleate reversal. Alternatively, the spin accumulation present at the interface can lead to instability out of a completely uniform magnetic state [16,17].

There has been considerable recent controversy due to interpretation of very large resistance changes using point contacts between two macroscopic FM entities as large values of DMR [21–23]. Making and breaking atomic scale contacts due to magnetostriction has been posited as an alternate explanation. Magnetostriction is unlikely to play a major role in our case. First, the resistance changes we observe are consistent with expected values of AMR and DMR [24]. Second, the magnetostrictive constants of Co, about 10^{-5}, would induce a change of about 0.01 nm for a 400 nm film. This small change is unlikely to make or break atomic bonds within the point contact.

From the contact resistance of about 30Ω, the contact size is about 5 nm using the Sharvin formula of $R = 4\rho l/3\pi a^2$ [25]. The nanodomain, expected to be comparable in size, is too small to be revealed by magnetic microscopy. Just as the case of trilayers, switching is inferred by the change in resistance. Because of the small contact, the absolute ΔR, from Fig. 1 is 0.7Ω, larger than what has been measured in trilayers at similar switching current. As pointed out previously, the actual value of ΔR is important for spin-based device applications [26]. It is also noted that the nanodomain, as shown in the Fig. 1 inset, is in fact a small magnetic bit, which can be written and erased on top of a uniform FM film by a switching current of about 2.5 mA as shown in Fig. 1. We have made 9 separate contacts with different contact resistances and found different switching currents. However, they share a common negative switching voltage of $-(64 \pm 8)$ mV with a common switching current density of $-(4.8 \pm 0.6) \times 10^9$ A/cm^2 and a common positive switching voltage $+(60 \pm 18)$ mV with a common current density $+(4.5 \pm 1.3) \times 10^9$ A/cm^2.

Fig. 3 shows the current-induced switching loops for another contact at various in-plane magnetic fields up to 9 T. The characteristics are similar for fields up to 0.4 T as shown in Fig. 3(a). At 0.45 T, the switching loop is shifted

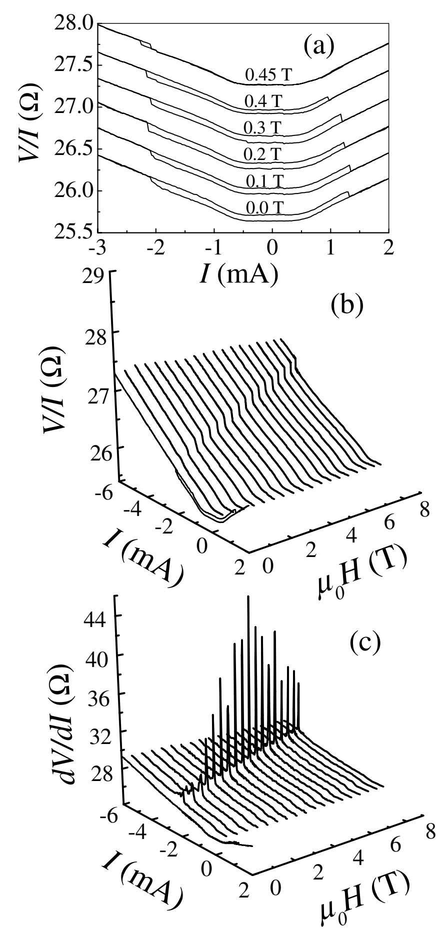

FIG. 3. Field dependence of resistance (V/I) in the field range of (a) 0 to 0.5 T, (b) 0 to 9 T, and (c) differential resistance (dV/dI) in the field from 0 to 9 T.

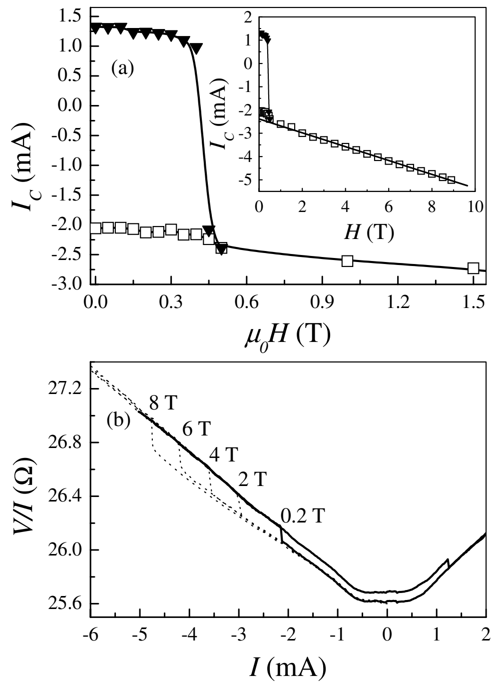

FIG. 4. (a) Switching currents as a function of magnetic field up to 1.5 T and up to 9 T (inset), (b) the (V/I)-I curves for 0.2 (solid line), 2, 4, 6, and 8 T (dashed lines).

to negative bias, and it is no longer bistable at zero current. At fields higher than 0.5 T, there is only a single resistance step in V/I [Fig. 3(b)] and a peak in the differential resistance dV/dI [Fig. 3(c)]. These high magnetic field features, similar to those observed in multilayers [4], trilayers [5,6], and single layers [10] with large perpendicular fields, have been previously attributed to spin waves (spin precession) as suggested by theory. The values of the switching current for positive polarity I_c^+ (solid triangles) and negative polarity I_c^- (open squares) are plotted as function of field in Fig. 4(a). In the high field regime, where the hysteretic switching loop is absent, I_c^- is defined from the position of the differential resistance peak. In general, a larger magnetic field reduces both I_c^+ and I_c^-, as shown in the inset of Fig. 4(a), because it favors parallel alignment of the two regions. The I_c^+ branch collapses onto the I_c^- branch at 0.5 T, which marks the boundary of the so-called low-field and high-field regimes. I_c^- varies smoothly between the two regimes, thus suggesting closely related mechanisms.

In Fig. 4(b), the (V/I)-I curves measured at several representative field values are plotted together. The hysteretic switching loop at 0.2 T is plotted as the solid lines with two branches of high and low resistances for antiparallel and parallel alignment of the two regions, respectively. The nonhysteretic curves in high fields are plotted as dashed lines, each of which has a single step at a specific negative bias. For each field, the resistances to the right and left of the step are the same as those of the lower and upper branch, respectively, of the low-field switching loop. This indicates that the final magnetic states in high fields below and above $|I_c^-|$ are identical to those in the low-field case. Thus, the differential resistance peak observed in high-fields is due to full reversal of the nanodomain, similar to recent conclusions made for trilayers [11,14], and *not* spin waves.

There have been reports of detection of signals attributable to spin waves and spin precession in multilayer at current values at and below the threshold ($|I| \leq |I_c^-|$) [14,27]. In a single Co layer, we have observed extra features in dV/dI at -3 mA at $|I| > |I_c^-|$ after the reversal shown in Fig. 1. These anomalies may be due to spin wave excitations. Finally, the slope of $|I_c^-|$ vs H in the inset of Fig. 4(a) has a value of 0.3 mA/T, showing the dominant role of current over field. A slightly larger current can easily overcome any fields, exchange bias field or a large external magnetic field.

In conclusion, we have demonstrated a new type of spin-transfer torque effect in a single ferromagnetic layer manifested as the inverse effect domain wall magnetoresistance. A nanodomain can be created and manipulated by the inhomogeneous current density within a ferromagnetic layer and detected by the change of domain wall magnetoresistance. In high magnetic fields, the differential resistance peak has been shown to be due to reversal of the nanodomain.

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[1] L. Berger, Phys. Rev. B **54**, 9353 (1996).
[2] J. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[3] Ya. B. Bazaliy *et al.*, Phys. Rev. B **57**, 3213(R) (1998).
[4] M. Tsoi *et al.*, Phys. Rev. Lett. **80**, 4281 (1998).
[5] E. B. Myers *et al.*, Science **285**, 867 (1999).
[6] J. A. Katine *et al.*, Phys. Rev. Lett. **84**, 3149 (2000).
[7] J.-E. Wegrowe *et al.*, Europhys. Lett. **45**, 626 (1999).
[8] J. Z. Sun, J. Magn. Magn. Mater. **202**, 157 (1999).
[9] F. J. Albert *et al.*, Phys. Rev. Lett. **89**, 226802 (2002).
[10] Y. Ji *et al.*, Phys. Rev. Lett. **90**, 106601 (2003).
[11] S. Urazhdin *et al.*, Phys. Rev. Lett. **91**, 146803 (2003).
[12] B. Ozyilmaz *et al.*, Phys. Rev. Lett. **91**, 067203 (2003).
[13] T. Y. Chen *et al.*, Appl. Phys. Lett. **84**, 380 (2004).
[14] S. I. Kiselev *et al.*, Nature (London) **425**, 380 (2003).
[15] W. H. Rippard *et al.*, Phys. Rev. Lett. **92**, 027201 (2004).
[16] M. L. Polianski and P. W. Brouwer, Phys. Rev. Lett. **92**, 026602 (2004).
[17] M. D. Stiles *et al.*, Phys. Rev. B **69**, 054408 (2004).
[18] V. Skumryev *et al.*, Nature (London) **423**, 850 (2003).
[19] T. Gredig *et al.*, J. Appl. Phys. **91**, 7760 (2002).
[20] L. Berger, J. Appl. Phys. **49**, 2156 (1978).
[21] N. Garcia *et al.*, Phys. Rev. Lett. **82**, 2923 (1999).
[22] N. Garcia *et al.*, Phys. Rev. Lett. **85**, 3053 (2000).
[23] J. J. Versluijs *et al.*, Phys. Rev. Lett. **87**, 026601 (2001).
[24] J. B. A. N. van Hoof *et al.*, Phys. Rev. B **59**, 138 (1999).
[25] Yu. V. Sharvin, JETP Lett. **48**, 984 (1965) [Sov. Phys. JETP **21**, 655 (1965)].
[26] J. Sun, Nature (London) **425**, 359 (2003).
[27] M. Tsoi *et al.*, Nature (London) **406**, 46 (2000).