Spin Torques in Point Contacts to Exchange-Biased Ferromagnetic Films

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Hysteretic magneto-resistance of point contacts formed between non-magnetic tips and single ferromagnetic films exchange-pinned by antiferromagnetic films is investigated. The analysis of the measured current driven and field driven hysteresis agrees with the recently proposed model of the surface spin-valve, where the spin orientation at the interface can be different from that in the bulk of the film. The switching in magneto-resistance at low fields is observed to depend significantly on the direction of the exchange pinning, which allows identifying this transition as a reversal of interior spins of the pinned ferromagnetic films. The switching at higher fields is thus due to a spin reversal in the point contact core, at the top surface of the ferromagnet, and does not exhibit any clear field offset when the exchange-pinning direction or the magnetic field direction is varied. This magnitude of the switching field of the surface spins varies substantially from contact to contact and sometimes from sweep to sweep, which suggests that the surface coercivity can change under very high current densities and/or due to the particular microstructure of the point contact. In contrast, no changes in the effect of the exchange biasing on the interior spins are observed at high currents, possibly due to the rapid drop in the current density away from nanometer sized point contact cores.

Index Terms — point contacts, spin transfer torque, spin-valves, exchange bias.

I. INTRODUCTION

The conductivity of point contacts formed between a non-magnetic needle (N) and a single ferromagnetic film (F) as well as a single ferromagnetic layer pillar, exhibit hysteresis which depends on the direction of the transport current through the N/F contact [1-6]. This hysteresis very much resembles the conventional F/N/F spin-transfer-torque (STT) hysteresis. It has been proposed [5,6] that the atomically thin layer at the magnetic surface (F), in which the exchange interaction is significantly reduced, acts differently from the spins in the bulk of the ferromagnetic film (Fb) where the exchange interaction is intact. The observed hysteresis would thus correspond to two different mutual spin orientations in Fs and Fb, e.g. parallel (P) and antiparallel (AP), affected by the STT of the current through the interface [7] or by an external magnetic field. This spin-valve type P-AP switching results in a hysteretic conductance due to the giant magneto-resistance effect.

The aim of the present work is to investigate the role of exchange pinning of the ferromagnetic film by an antiferromagnet in the observed surface spin-valve effect, as well as the influence of currents of extremely high density that can be produced in point contacts [8] on the exchange coupling at the ferromagnetic/antiferromagnetic interface.

II. EXPERIMENTAL

The samples in this study were thin film structures of type AF/F/N, Fe50Mn50(5 nm)/Co(4 nm)/Au(3 nm), and type F/N, Co(100 nm)/Cu(3 nm)/Au(4 nm), deposited on Si substrates buffered with 100 nm thick layer of Cu serving as the bottom electrode (Fig. 1a), and Au or Cu+Au as a capping layer. The exchange pinning was set in by slowly cooling the films in the field of ~1 kOe from above the Neel temperature of the AF (~450 K for Fe50Mn50) to room temperature. All measurements of R(V) and R(H), where R=dV/dI is the differential resistance, were performed by lock-in technique with low-current density away from nanometer sized point contact cores.

Manuscript received October 31, 2009. Corresponding author: V. Korenivski (e-mail: vk@kth.se).
Digital Object Identifier inserted by IEEE.

Fig. 1. (a) Layout of point contacts to magnetic sandwich films and the electrical circuit of the experiment. The point contact is created between a Cu tip and the top surface of a Co film capped with a 3 nm protective layer of Au. The bottom surface of Co is exchange coupled to antiferromagnetic Fe50Mn50 film. (b) The surface spin-valve model assumes that the Co spins at the top N/F interface form a spin-subsystem able to rotate with respect to the interior spins under STT or external field. The boundary between the surface spin layer and the bulk of the F film is a domain wall of thickness comparable to the interatomic distances.
frequency modulation of about 100 μV at T=4.2 K. Some of the experiments were performed on Si/SiO/Cu/FeMn/CuFeB/Cu F/AF stacks. The geometry of the point contacts was of type needle-anvil [5], as shown in Fig. 1a, measured using the two-point scheme: the tip at (+I, +V), and the Cu electrode at (−I, −V).

Comparative tests using a three-point electrical scheme [tip at (+I, +V), buffer electrode at (−I, −V')] showed only insignificant changes in R(V), with offsets in V from the small series resistance introduced of no more than a few % for typical point contacts of 10 Ohm in resistance (~10 nm diameter contact core).

III. RESULTS

Fig. 2 shows R(V) and R(H) for a point contact to a 100 nm thick Co film without the AF layer at the bottom surface (a,b), as well as for a point contact to a Co film for which the buffer contained an AF layer spaced from the ferromagnetic Co by a 10 nm Cu layer sufficient for exchange-decoupling the F and AF layers (c,d) [9]. R(V) for both contacts [Fig. 2 (a,c)] shows resistance hysteresis driven by the STT effect [7] of the current through the contacts. The STT rotates the surface spins with respect to the interior spins, which results in giant magnetoresistance at the interface. The magnitude of the corresponding magnetoresistance in R(H), shown in (b,d), is approximately the same as in R(V). This confirms that both the current- and field-drive hysteretic transitions originate from the spin reversal of the same magnetic element, in this case the F sub-layer at the top surface of the ferromagnetic film. The data in Fig. 2(b,d) additionally show that, in the absence of exchange pinning, the hysteresis in R(H) is practically symmetric about H=0.

Fig. 3(b,d,f) shows R(H) for point contacts to exchange-pinned Co films, for three different orientations of the applied field H with respect to the pinned magnetization of the F/AF layer M. It is seen that the direction of the exchange offset depends on the mutual orientation of M and H (b,f), while for H perpendicular to M the hysteresis loop is approximately symmetric in field. The characteristic switching fields are different from the exchange pinning field of H_EB ≈ ±0.5 kOe, as seen in Fig. 3 (b,f). The shift along H for the transitions at low-field changes as a function of the applied field orientation. This suggests that the interior of the Co film (F sub-layer) switches first since the influence of the exchange coupling on the spins at the distant top surface (F spin sub-layer) should be negligible. We can thus conclude that the switching of the surface spins in the point contact core takes place at higher fields and is seen as the outer hysteretic transition in R(H) in (b,d,f). The magnitude of the switching field of this surface spin layer varies significantly from contact to contact and sometimes from run to run, showing a much larger variation than that for F. This suggests that the magnetic coercivity in the contact core is affected by the nanoscale morphology of the contacts as well as the very high current densities driven through the contacts.

The hysteresis in R(V) for the same contacts measured in the absence of any external field is shown in Fig. 3(a,c,e) and is due to the STT effect on the surface spin-valve at the N/F interface [5]. The low-resistance P state of the F and F sub-layers is formed when F switches typically at positive polarity of the driving current, corresponding to the spin-polarized current flowing from the ferromagnetic film F through the nonmagnetic tip through the surface spin layer F. In Fig. 3e, the AP-P switching occurs at a small negative voltage and is a rather rare event, likely due to a modification of the F magnetic structure caused by the mechanical pressure of the needle and/or exchange-bias field. Incidentally, |V| for the AP-P transition is smaller than |V| for the reverse P-AP transition (|V|<|V|), visible around ~30 mV.

We note that the three-level resistance seen in multiple scans in Fig. 3(c) is attributed to a circular spin vortex in the surface spin layer F, promoted by the Oersted field of the current in the point contact core [6].

Thus, the magnetoresistance R(H) of point contacts to ferromagnetic films exchange-pinned by antiferromagnets exhibit the effect of exchange offset which depends on the mutual orientation of H and M, as illustrated in Fig. 3 (b,d,f). The switching in the interior of the ferromagnet occurs at lower fields (H) than the switching of the surface spin layer (H). The origin of this higher switching field can potentially be a higher coercivity due to the morphological imperfections.
Moreover, $H$ can change during the process of the magnetization reversal. Contact indicates that the coercivity of the surface spin layer varies in a wide range for nominally similar tip-surface contacts. The sometimes observed variation in $H_S$ from sweep to sweep for the same contact indicates that the coercivity of the surface spin layer can change during the process of the magnetization reversal. Moreover, $H_S$ can be varied under the action of very high fields, 1-2 kOe. Hysteretic magneto-resistance is observed also in $R(V)$ due to the effect of spin-transfer-torques on the surface spins, and is of similar magnitude as that in $R(H)$, around 1-2%. Multiple scans in (c) show an example of a tri-stable spin state, which was interpreted in [6] as due to a spin vortex. The long tilted arrows show the direction of the voltage or field sweep.

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