Point-contact studies of current-controlled domain switching in magnetic multilayers

E. B. Myers[a] and D. C. Ralph
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853

J. A. Katine, F. J. Albert, and R. A. Buhrman
School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853

We present measurements demonstrating current-induced magnetic domain switching, and also other magnetic excitations, in point-contact devices containing alternating ferromagnetic (F) and noble metal (N) layers, for perpendicular currents $\sim 10^9$ A/cm^2. For F/N/F trilayers in which one F layer is much thinner than the other, we can controllably switch the magnetic moments in the two F layers parallel with a current bias of one sign, and switch them antiparallel with a reversed current. For thicker magnetic films, and for thin films in the presence of a saturating magnetic field, we observe nonhysteretic current-induced changes in resistance, which can be understood as current-induced spin-wave excitations. These observations are in agreement with a model of current-induced magnetic reorientations caused by local exchange forces between conduction electrons and the magnetic moments. © *2000 American Institute of Physics.*
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All ferromagnetic data storage and magnetic sensing devices currently in use operate through the application of a magnetic field to reorient magnetic elements within the device. Several recent theoretical papers however, have predicted that it may be possible for magnetic elements in multilayer devices to instead be manipulated by a mechanism, called ''spin transfer,'' based on the local exchange interaction between electrons and magnetic moments rather than by a magnetic field.[1–3] This mechanism has been predicted to excite spin waves within the layers[1–3] or even cause full domain reversal.[2] Previous experimental studies have seen current-induced changes in the resistance of Cu/Co multilayers[4,5] and granular alloys,[4] nickel nanowires,[6] and manganite junctions,[7] but the nature of the excitations has not been clear. We have performed current-perpendicular-to-the-plane (CPP) transport measurements on ferromagnetic/ nonmagnetic/ferromagnetic (F/N/F) trilayer devices using a point-contact geometry, and have observed current-induced domain switching and spin-wave excitations.[8] The observations provide strong evidence that the spin-transfer effect, governed by local exchange, is the dominant interaction in these devices. Very recently, these results have been confirmed and extended in studies of F/N/F trilayer devices in a pillar geometry $\sim$ 100 nm in diameter, for which switching occurs at significantly lower current densities.[9]

The underlying mechanism of spin transfer is the spin-dependent scattering of conduction electrons that occurs at a normal metal/ferromagnet interface.[2] First, consider the simple case of a spin-polarized current incident on a single ferromagnetic layer, with the direction of current perpendicular to the layer [Fig. 1(a)]. We assume that the layer is uniformly magnetized parallel to the interfaces, in the direction $\vec{S}_1$, while spins of the incident electrons are spin polarized at an angle θ to $\vec{S}_1$. Due to exchange, electrons will be scattered differently by the layer depending on the relative spin orientations. In the limiting case of 100% spin filtering by the magnetic layer, which is predicted to be essentially correct for interfaces such as Cu/Co,[10] the components of the electron wave function having spin aligned with the moments (spin-up) will be fully transmitted through the layer, while spin-down components will be completely reflected.
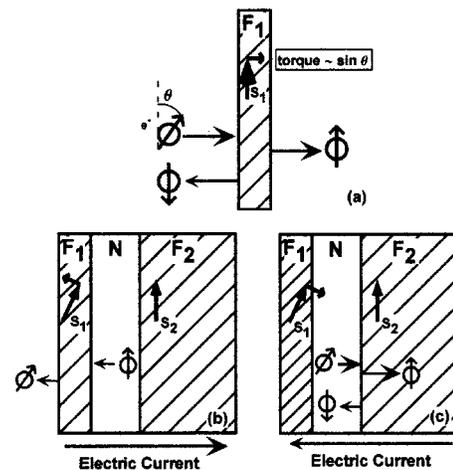

FIG. 1. Schematic of spin-transfer model. (a) A current spin polarized at an angle θ to the moment direction $\vec{S}_1$ of a thin ferromagnetic layer F_1 will exert a torque (proportional to sin θ) on the layer moments, due to the spin-dependent scattering of the conduction electrons at the interface. The direction of the torque is so as to align the moments with the current polarization. When a second, thicker layer F_2 is added the effect is asymmetric with the current. (b) Electrons flowing from layer F_2 to layer F_1, and initially polarized along the moment direction $\vec{S}_2$ exert an aligning torque on F_1, as in (a). If the current is reversed (c), spins antialigned with $\vec{S}_2$ will be reflected from the $N-F_2$ interface and return to F_1 exerting a torque *opposite* to that in (b); thus an antialigned configuration of the moments is stable, and an aligned configuration unstable.

[a]Electronic mail: ebms@cornell.edu

Calculating the net flow of angular momentum into and away from the magnetic layer, it is easy to see that any component of angular momentum perpendicular to $\vec{S}_1$ ($\propto \sin\theta$) carried by the incident electrons must be deposited in the magnetic layer.[2] This results in a torque, proportional to the current, that acts to align the moment with the polarization of the incident current. The torque is still present even if the incident current is not 100% spin polarized, or if the magnetic layer is not a perfect filter.

When a second layer is added, the spin-transfer effect generates an asymmetry with respect to the direction of current. Figure 1(b) shows a F/N/F trilayer, with normal metal leads; we assume (here, as well as in the experiment itself) that one of the magnetic layers (F_2 in the figure) is thick enough so that the magnetic moments are insensitive to the exchange torque as compared with the other, thinner layer (F_1). In the case of right-going current (left-going electron flow) shown in Fig. 1(b), electrons will emerge first from F_2 polarized along $\vec{S}_2$, where $\vec{S}_2$ is the local moment direction of the thick layer. When they impinge upon F_1, they exert a torque which, as described above, tends to align $\vec{S}_1$ with the spin polarization direction of the current (i.e., $\vec{S}_2$), so that a parallel configuration of the two layers is stable. If the current is reversed [Fig. 1(c)], the electrons are now polarized first along $\vec{S}_1$. They then scatter off of F_2, which transmits the portion of the electron wave aligned with $\vec{S}_2$, and reflects a portion which is antialigned. These reflected electrons return to layer F_1, where, due to the $\sin\theta$ symmetry of the spin-transfer effect, they exert a torque *opposite* in direction to that depicted in Fig. 1(b). For this sign of current, then, spin transfer causes $\vec{S}_1$ to rotate *away* from $\vec{S}_2$, so that antiparallel alignment is stable and parallel alignment unstable. This instability may take the form of a dynamical precession (spin-wave), or a switching of the moment to a stable antiparallel orientation.

In order to induce a magnetic excitation the torque must overcome exchange, anisotropy, and damping effects, which in spin-transfer theory requires high current densities,[11] on the order of $10^7 - 10^9$ A/cm^2. To achieve this, we employ a point-contact geometry [Fig. 2(a)]. First, a bowl-shaped hole, 5–10 nm in diameter at its narrowest point, is etched in a suspended insulating silicon nitride membrane, using a technique described elsewhere.[12] A nonmagnetic metal (usually Cu) is evaporated onto the bowl side of the hole, and then the trilayer is evaporated on the other side of the device. Current densities on the order of 10^9 A/cm^2 are achieved in this geometry with the application of a few milliamps of current bias, without damage or irreversible alteration of the devices. Both dc and differential resistance measurements are performed on the device, with a lock-in amplifier used for the latter. In what follows, positive current is defined as electrons flowing from the thin ferromagnetic layer into the thick layer.

Figures 2(b) and 3(a) show the differential resistance as a function of current bias at 4.2 K, for trilayers composed in the order t nm Co/4 nm Cu/100 nm Co, where t is the thickness of the thinner ferromagnetic layer [F_1 in Fig. 2(a)]. For the thinner Co layers [$t = 4$ nm in Fig. 2(b)], a hysteresis loop
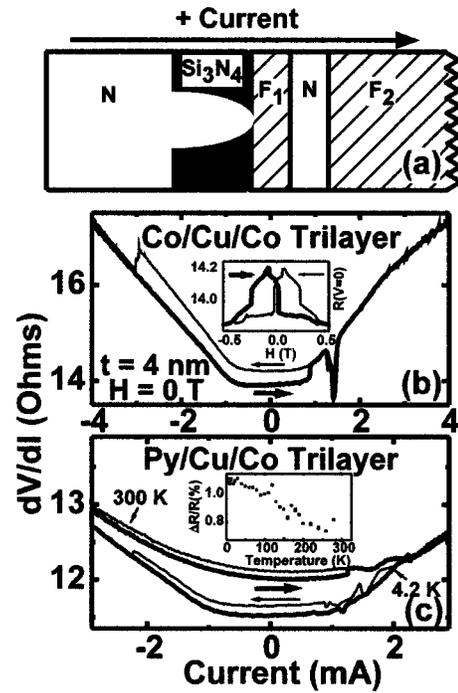

FIG. 2. (a) Device schematic. (b) Co/Cu/Co trilayer, with the thin layer F_1 having thickness $t = 4$ nm. The current-induced domain reversal agrees in magnitude with the field-induced domain reversal seen in magnetoresistance measurements (b, inset). (c) Py (=Permalloy)/Cu/Co trilayer demonstrating stable switching up to room temperature. The 300 K curves have been shifted down by 2.8 Ω to fit in the figure. The fractional change in resistance $\Delta R/R$ decreases with temperature in a manner similar to other CPP magnetoresistance studies of multilayers.[13]

is seen in the differential resistance as the current is swept, which corresponds to a hysteretic change in the dc resistance of the device. This observation can be understood as a current-controlled switching between two stable states for a domain in the thin Co layer near the point contact. As the current is swept to a sufficiently large positive value I_{c+} [thick curve in Fig. 2(b)], spin-transfer effects will switch the thin-layer moments near the point contact into a stable configuration antiparallel to the thick-layer moments. This is consistent with our observation that the resistance jumps to a higher value. As the current is reduced [thin curve in Fig.
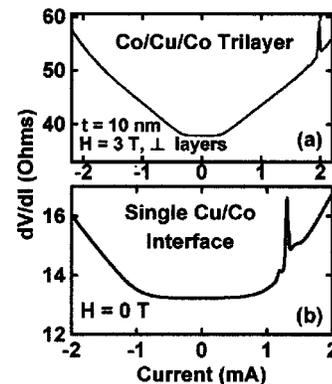

FIG. 3. (a) Data as in Fig. 2, but for $t = 10$ nm and $H = 3$ T, and (b) for a single Cu/Co interface. A hysteretic domain reversal is no longer seen; instead, features corresponding to spin-wave excitations are present, for only one sign of current bias.

2(b)], the thin-layer domain remains in this stable state until a sufficient negative current I_{c-} is reached, where the opposite spin-transfer torques switch the moments back into a configuration aligned with the thick-layer moments.

Our identification of the hysteresis as domain switching is supported by zero current-bias magnetoresistance measurements [Fig. 2(b), inset]. Here a field parallel to the layers has been applied; as the field is swept, domains in each layer near the point-contact region flip between antiparallel and parallel configurations, due to the differing coercive fields of the two layers. The change in resistance measured here agrees with the measured resistance change caused by the current-induced switching.

The hysteresis did not persist to room temperature for the Co/Cu/Co trilayers measured. However, in a 4 nm permalloy/4 nm Cu/100 nm Co device made in the same fashion, the switching remained stable at zero current bias up to 300 K [Fig. 2(c)]. The fractional change in resistance, $\Delta R/R$, where ΔR is the difference in resistance between the two stable magnetic states at zero current bias, and R (in keeping with the convential definition of the giant magnetoresistance ratio) is the resistance of the parallel-moment state, is shown in the inset to Fig. 2(c). This ratio decreased with temperature in a manner agreeing qualitatively with CPP multilayer measurements.[13] The reason why the switching effect is not stable at room temperature in most devices is likely that intralayer coupling of the flipped domain to the rest of the thin film makes the reversed orientation unstable to thermal fluctuations; similar current-induced switching studies in Co/Cu/Co nanopillars,[9] in which the magnetic regions are isolated domains, are all stable at room temperature.

The hysteresis disappears for magnetic fields, H, comparable to the fields which align the layers in the magnetoresistance measurements. What remains are nonhysteretic features which are also seen in the samples with thicker layers [e.g., $t = 10$ nm in Fig. 3(a)], where intralayer coupling prevents stable switching even at low temperature, and also in samples consisting of a single Co–Cu interface [Fig. 3(b)]. The $t = 10$ nm sample data were taken with H applied perpendicularly to the layers. Here, as in other studies,[5,9] features occur only for positive current bias, corresponding to the sign of the thin-layer instability in the spin-transfer model. In addition, these features are usually positive spikes in the differential resistance (jumps in the dc resistance), indicating that they indeed correspond to deviations of the thin-layer moments from parallel alignment with the thick layer. However, the presence of similar features in the single-interface samples suggests that such excitations can also be generated in the thick layer, in contrast to the assumption of the simplest spin-transfer model. Bazaliy *et al.*[3] predict that current densities around 10^9 A/cm^2, generated by our point-contact geometry, can excite spin excitations within a ferromagnet.

The presence of such excitations in the devices which also demonstrate hysteresis [Fig. 2(b)] helps to confirm this understanding of the thick-layer excitations. In these cases the features, located at higher bias than the hysteretic jumps, are usually dips in the differential resistance. This is consistent with a spin-wave excitation in the thicker layer at this higher current, as such an excitation would necessitate a deviation from the antiparallel alignment of the layers brought about by the lower switching current, and therefore would result in a lower dc resistance. The magnitude of the change in dc resistance corresponding to the feature in Fig. 2(b) is about one third of the change corresponding to the hysteretic jump, indicating that the thick-layer moments near the point-contact region have not fully reversed, but instead may be in some state intermediate between full alignment and anti-alignment with the thin-layer moments, e.g., a precessional state.[2,9,11]

To summarize, we have performed CPP transport measurements on F/N/F trilayers, using a point-contact geometry to generate current densities above 10^9 A/cm^2. For thinner magnetic layers, moments in the two ferromagnetic layers can be forced into an antiparallel alignment with a current pulse of one sign, and aligned parallel with a current pulse of the opposite sign. The sign of the switching agrees with spin-transfer theory, in which exchange is the dominant interaction between the flowing electrons and the magnetic moments. This switching can be stable at room temperature, indicating that new kinds of nonvolatile magnetic memory devices could be made employing the effect. The switching disappears both at fields above the saturation field and if the thin ferromagnetic layer is made thicker; instead, nonhysteretic features appear which are consistent with spin-wave excitations induced by spin transfer.

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