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Spin-transfer-induced domain wall motion in a spin valve

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We have studied the current-induced displacement of a domain wall (DW) in the permalloy (Py) layer of a Co/Cu/Py spin-valve structure. At zero and very small applied fields (<10 Oe), the displacement is in opposite direction for opposite dc currents, and the current density required to move DW is of the order of a few 10^6 A/cm^2. At higher applied magnetic fields, the DW motion, even though triggered by the current, has its direction controlled by the field. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1687293]

Since its theoretical prediction in 1996 by Slonczewski and Berger,[1,2] the spin-transfer effect has been studied thoroughly, both experimentally and theoretically. From the application point of view, the use of the spin-transfer effect to switch magnetic devices such as MRAMs could allow one to decrease the energy cost compared to the classical switching induced by an Oersted field. From the theoretical point of view, investigation of the effect has already led to a better understanding of the interaction between a spin polarized current and the local moments. Its dependence on spin accumulation and current polarization should soon be elucidated.[3]

The first experiments, concerning injection of a high dc spin polarized current (of the order of 10^7 A cm^{-2}) through either point contacts,[4] nanowires,[5] or nanopillars in a CPP geometry,[6–8] follow the scheme proposed by Slonczewski. A thick ferromagnet is used to polarize the spin current that will flow through a thin ferromagnet, and influence the direction of its magnetization.

It has been recognized recently that, following the pioneer experimental work of Berger and co-workers,[9] the spin-transfer effect could allow one to move a domain wall (DW) by injection of a high dc current. The investigation of the current-induced DW motion has been performed either by imaging samples (using Kerr effect or MFM) before and after the current injection,[9–12] by detecting the DW position using electrical measurements,[13,14] or combining both techniques.[15]

Our experimental study of the spin-transfer-induced DW motion is original in two ways. First, we investigate the switching of a spin valve and not only a thin magnetic film by current-induced DW motion. The CIP-GMR effect allows an accurate determination of the DW position and displacement by electrical measurements while the dc current is injected. Second, we demonstrate that back and forth motion of a DW is possible by injection of a dc current at very small applied magnetic fields.

Our samples are 300 nm wide and 20 μm long stripes patterned by electron-beam lithography using a lift-off technique. The spin valves, deposited by sputtering, have a final structure/CoO (30 Å)/Co (70 Å)/Cu (100 Å)/Py (50 Å)/Au (30 Å). The top Au electrodes are processed by UV lithography. All measurements were performed at room temperature.

In Fig. 1, we show a typical CIP-GMR minor cycle associated with the reversal of the magnetization in the permalloy (Py) layer, i.e., with the motion of a DW from one end of the Py stripe to the other one. The plateaus are due to the pinning of the DW on natural defects in the Py stripe. We emphasize that the series of plateaus on the CIP-GMR curve are highly reproducible. As shown for the left half of the cycle, a DW remains pinned on the same defect when the field is brought back to zero. We can therefore start an experiment at zero field with the DW pinned in one of the three positions (sketched) corresponding to the resistance levels 1, 2, and 3. The results presented below correspond to experiments performed with a DW initially pinned in the configu-

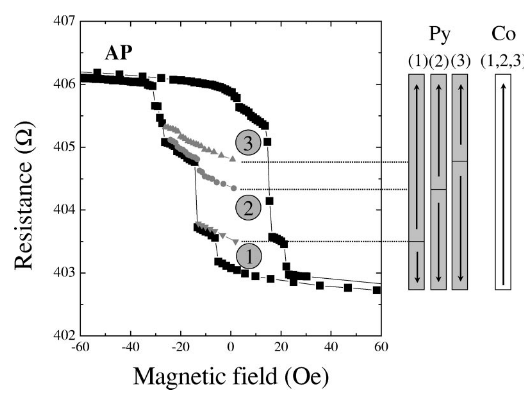

FIG. 1. (■), GMR minor cycle associated with the reversal of the Py layer of the Co/Cu/Py trilayer at $T=300$ K. The field is applied along the stripe. The Co magnetization is pinned in the positive field direction. (□), (▽), (○), variation of the resistance when the cycle is stopped at one of the plateaus and the field is brought back to zero. Also shown are the DW position in the Py stripe and the magnetic configuration corresponding to the levels 1, 2, and 3).

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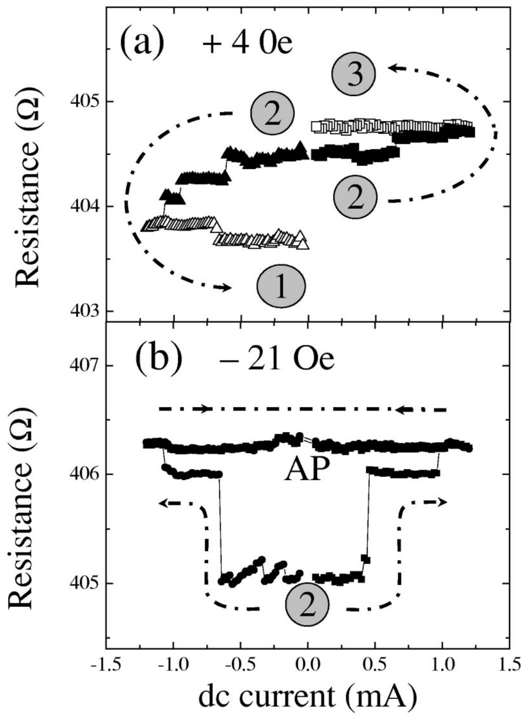

FIG. 2. Resistance vs current in constant field H along the stripe. (a) $H=4$ Oe (■), motion from 2 to 3 with a positive current; (▲), motion from 2 to 1 with a negative current); (b) resistance vs current for $H=-21$ Oe. The numbers 1, 2, and 3 refer to the DW configurations and corresponding resistance levels of Fig. 1. A small contribution ($\sim I^2$), due to the Joule heating ($\Delta T \simeq 5$ K), has been subtracted for clarity.

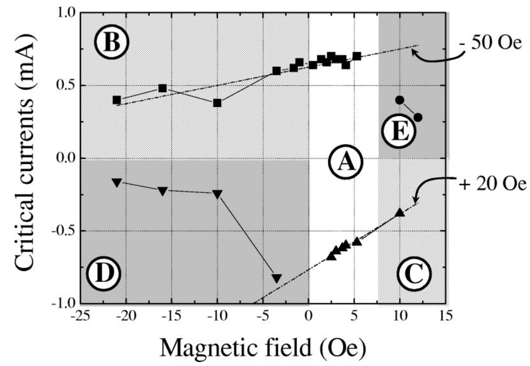

FIG. 3. Critical currents vs applied magnetic field. The initial state corresponds to plateau 2. (■) (●) corresponds to positive critical currents leading to motion in the direction of the AP plateau (P plateau). (▲) (▼) corresponds to negative critical currents leading to motion in the direction of the P plateau (AP plateau). The dotted lines are fits of the experimental data. Their intersection with the $I=0$ axis corresponds to -50 and $+20$ Oe magnetic field.

ration 2. The experiments are performed by varying the current at zero or low field (parallel to the stripe).

Figure 2(a), obtained with an applied field of 4 Oe, shows the typical resistance versus current curves obtained when the field is in the range 0–7 Oe. Starting from the DW in position 2, we can move the DW to position 3 by increasing the current above the positive critical value $j_{c2}^{+}(4\ \mathrm{Oe}) = +0.65$ mA and decreasing it back to zero. Alternatively, the DW is moved in the opposite direction (from 2 to 1) with a negative current exceeding $j_{c2}^{-}(4\ \mathrm{Oe}) = -1.1$ mA. Plateaus 1 and 2 (2 and 3) are separated by 0.8 Ω (0.47 Ω), corresponding to a distance of 5.9 μm (3.3 μm). To calculate the involved current densities, we have to take into account the repartition of the current in the trilayer system. In an intermediate situation (mean free path of the order of the Co and Py thickness, consistently with the small but nonzero GMR, and certainly some current channeling in Cu by specular reflections), the estimated current density in Py is of the order of a few 10^6 A/cm^2. This is almost an order of magnitude smaller than the currents required for the magnetization reversal in pillar-shaped multilayers.[6–8]

Out of the low field range described above, the behavior becomes more complex. An example of experimental result is shown in Fig. 2(b) for $H=-21$ Oe favoring an antiparallel (AP) configuration. A positive current moves the DW from position 2 to the end of the stripe (AP resistance level), which is consistent with the low field result. On the other hand, the motion is not reversed for negative currents and the final state is still the AP configuration. A similar behavior for large positive fields is observed, with a motion towards a more parallel (P) configuration. We can therefore conclude that, out of the low field range, the current is still able to unpin the DW, but the direction of the DW motion is now controlled by the applied field.

We have plotted in Fig. 3 the critical currents corresponding to the first instability of the magnetic configuration 2 versus the applied magnetic field. In the central zone labeled A, (i.e., in the 0–7 Oe low field range), positive currents (■) lead to a DW motion towards the AP plateau. Negative currents (▲) lead to motion in the opposite direction. In the high negative field region, corresponding to zones B and D, both current signs lead to DW motion towards the AP plateau. It is interesting to note the continuity between zones A and B, both regions in which the current and field tend to induce the same direction of motion for the DW. On the contrary a huge discontinuity appears between zones A and D, suggesting that the conflict between field and current effects leads to a change in the current-induced DW motion mechanism. A symmetrical behavior is observed in the high positive field region (zones C and E). As the behavior is linear in zones A and B, as well as A and C, we have fitted the experimental data by $I_c(H) = I_c(0)(1 + H/H_0)$ (dotted lines in Fig. 3). The values for H_0 are found to be -50 and $+20$ Oe. $I_c(0)$ corresponds, as previously mentioned, to a current density of a few 10^6 A cm^{-2}.

The Oersted field generated by the current (20 Oe) is in the DW plane and thus cannot favor the motion in one or the other direction.[16] Our results are consistent with the spin-transfer mechanism introduced by Berger[17] and more recently Tatara *et al.*,[18] in the case of adiabatic DWs. The position of the DW is determined by two components: X along the axis of motion (or axis of the stripe) and ϕ the out of plane angle of the average local moments in the wall. A magnetic field applied along X leads to an energy variation of the domain wall with X, whereas the spin-transfer torque leads to a variation of energy with ϕ. The spin-transfer torque is in fact equivalent to the torque that would be exerted by a magnetic field applied in the out of plane direction of the stripe and localized within the DW.[19] The result of these calculations (performed at zero magnetic field) gives the following critical current density: $j_c = (\lambda e/\hbar P)\,\mu_0 M_s^2$, where e is the electron charge, M_s the saturated magnetization, λ the DW width, and P the spin polarization of the current. For $j < j_c$, the current cannot drive the wall, but just displaces it by approximately $\Delta X = (\lambda/2\alpha)\arcsin(j/j_c)$. We have performed micromagnetic simulations using the OOMMF software,[20] which have allowed us to estimate the width of the DW in our samples to $\lambda \approx 200$ nm. Using $M_s \approx 800$ kA m^{-1} for Py, and $P=1$, we calculate that $j_c \approx 2.5 \times 10^{10}$ A cm^{-2}. This value is four orders of magnitude above our experimental critical currents, which implies, in the frame of these models, that we are not in the wall-streaming regime. In this case, the calculated displacement amplitude ΔX is 20 nm with a damping parameter α of 0.001. This value cannot explain our experimental results where ΔX is of the order of the micron. In the case of spin transfer in nanopillars, the expression of the critical current at zero field is $j_c(\text{pillars}) = (t\alpha e/\hbar P)\,\mu_0 M_s^2$, where t is the thickness of the thin ferromagnet. Thus $j_c(\text{DW})/j_c(\text{pillars}) \approx \lambda/\alpha t \approx 10^4$ with $\lambda \approx 100$ nm, $t \approx 10$ nm, and $\alpha \approx 0.001$. This huge difference in critical currents between both structures does not correspond to experimental results, neither in our case, nor in other groups.[10–12,14,15] Moreover, from the linear fits in Fig. 3, it seems that the field dependence of the critical currents scales with the longitudinal anisotropy constant rather than with the perpendicular one. This is in contradiction with a mechanism where the spin torques acts on the out of plane ϕ component of the wall, thus having to counterbalance the huge demagnetizing field, and not the small in plane anisotropy constant.

Waintal and Viret[21] have recently proposed a model in which they calculate locally in the DW the components of the spin induced torque. In addition to the aforementioned torque, they emphasize the existence of an oscillatory component arising from the precessional motion of the spin current around the local spins in the wall. This component leads to a deformation of the wall, thus facilitating its depinning. Introducing this additional term in the previous calculations should consequently decrease the theoretical critical currents. The induced deformation of the wall could also explain the observed behavior in zones D and E of Fig. 3: the depinning of the wall is triggered by the oscillatory component of the spin-transfer torque, and then the wall is driven by the predominant action of the magnetic field.

In conclusion, we have evidenced current-induced back and forth switching of a DW in a spin valve, at low magnetic fields $(0 < H < 7$ Oe$)$. The involved current densities are of a few 10^6 A cm^{-2}. At higher magnetic fields, the current still triggers the depinning of the wall, but its direction of motion is then imposed by the field. Our experimental critical current densities as well as their dependence with the applied magnetic field are not in agreement with the theoretical predictions of Berger[17] and Tatara *et al.*[18] Nevertheless, by taking into account in these calculations the oscillatory component of the spin-transfer torque introduced by Waintal and Viret,[21] these discrepancies should disappear. The induced deformation of the wall would in effect decrease the theoretical critical current densities, and could also explain our high field behavior.

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