Switching a spin valve back and forth by current-induced domain wall motion

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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 field. The displacement is in opposite direction for opposite dc currents, and the current density required to move DW is only of the order of 10^6 A/cm^2. For $H=3$ Oe, a back and forth DW motion between two stable positions is observed. We also discuss the effect of an applied field on the DW motion. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1594841]

Switching the magnetic configuration of a microdevice by spin transfer from a spin-polarized current, rather than by applying an external field, is the central idea of a present extensive research.[1–7] In 1996, Slonczewski[1] showed that the magnetic moment of a ferromagnetic layer can be reversed by injecting a spin-polarized current into this layer. This prediction has been convincingly confirmed by series of experiments on pillar-shaped magnetic multilayers,[3–5] nanowires,[6] or nanocontacts.[7] However, the current density required in the existing experiments is relatively high, of the order of 10^7 A/cm^2, and some reduction of this density is necessary for practical applications.

Another way to change a magnetic configuration is by current-induced motion of a domain wall (DW). DW-drag by a current has been predicted by Berger[8] and its theory has been recently revisited by Waintal and Viret.[9] When a spin-polarized current goes through a DW, the torque, resulting from the interaction of the conduction electron spins with the exchange field in the DW, progressively rotates the spin polarization of the current. Reciprocally, the spin-polarized current exerts an exchange torque on the magnetization within the DW, which is the origin of the DW motion predicted by Berger.[8]

Freitas and Berger[10] have obtained some experimental evidence of DW-drag by using Kerr microscopy to detect the DW position. In recent similar experiments Koo *et al.*[11] have also measured DW displacement due to current pulses by imaging the DW by MFM before and after current pulses. The main features in these two sets of experiments are that the direction of the the DW motion is reversed when the direction of the current pulses is reversed, and that the order of magnitude of the current pulses needed to move the DW is about 10^7 A/cm^2.

In recent experiments on Co/Cu/Py spin valves,[12] we have also found that a dc current can switch the magnetic configuration of the spin valve by moving a DW in the permalloy (Py) free layer. We observed that a DW can be moved away from an artificial pinning center (notch) when the current density exceeds a threshold value of the order of 10^7 A/cm^2. However, the mechanism of the DW displacement was not completely clear. In fact, the DW could not be displaced at zero field, but only by combining current and applied field. Also, the motion direction was determined by the field direction and not reversed when the current was reversed. These results suggested a more complex mechanism than described by Berger,[8] with a possible effect of the applied field on the DW distorted by the current. In this letter we present much clearer results obtained on spin valves but with weaker DW pinning. The displacement of the DW is obtained at zero field, in opposite directions for opposite current directions and with definitely lower current densities.

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. In contrast with our previous experiments,[12] the only pinning centers for the DW in the Py soft layer are natural defects of the stripe. All the measurements were performed at room temperature.

In Fig. 1 we show a typical giant magnetoresistance (GMR) minor cycle associated with the reversal of the magnetization in the 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 defects in the Py stripe. We emphasize that the series of plateaus on the GMR curve is 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 later correspond to experiments performed with a DW initially pinned in configuration 2. The first series of experiments are performed by varying the current at zero or very low field (parallel to the stripe). In another series of experiments, we study the influence of a

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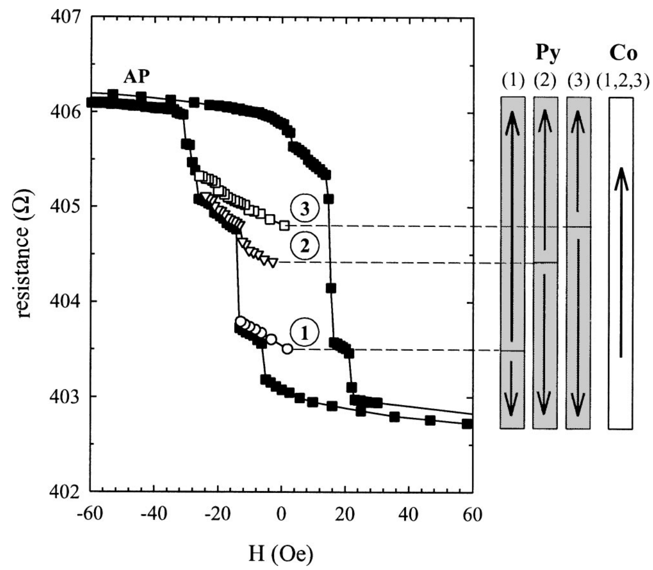

FIG. 1. (■)—GMR minor cycle associated with the reversal of the permalloy layer of the Co/Cu/Py trilayer at $T=300$ K. The field is applied along the stripe. The magnetization of the Co layer is pinned in the positive field direction. (□, ▽, ○)—variation of the resistance when the cycle is stopped at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

larger bias field on the current-induced DW motion.

In Fig. 2 we present results obtained by varying the dc current at constant field close to zero (4 and 3 Oe). As shown in Fig. 2(a), starting from the DW in position 2, we can move the DW to position 3 by increasing the current above the positive critical value $j_{c2}^{+}(4\ \text{Oe})=+0.65$ 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 $j_{c2}^{-}(4\ \text{Oe})=-1.1$ mA (in our notation j_{cn}^{+} and j_{cn}^{-} are the critical currents required to move the DW from position n to positions $n+1$ and $n-1$, respectively). The same type of behavior is observed for all applied fields between 0 and 7 Oe. However, even in this very small field range, there is some field dependence of the critical currents: $j_{cn}^{+}(H)$ $[j_{cn}^{-}(H)]$ decrease when H decreases (increases) and favors a DW motion from n to $n+1$ $(n-1)$.

Figure 2(b) presents an example of back and forth DW motion, namely the motion from 2 to 3 with positive dc current and a return to 2 with a negative dc current. The obvious conditions for this back and forth motion are $j_{c2}^{+}(H)<j_{c3}^{+}(H)$ (required to stop the first motion in configuration 3) and $|j_{c2}^{-}(H)|>|j_{c3}^{-}(H)|$ (necessary for the return to configuration 2). It turns out that these conditions are satisfied for the pinning centers 2 and 3 of our sample, at least for $H=3$ Oe.

The behavior observed in the field range close to zero (approximately, $0<H<7$ Oe) can be summarized as follows. A DW can be displaced between pinning centers and, in agreement with what is predicted for a displacement by Berger's mechanism,[8] its motion is in opposite directions for opposite currents. The dc current density needed to move the DW is of the order of 10^6 A/cm^2, that is an order of magnitude smaller than the currents required for the magnetization reversal in pillar-shaped multilayers.[3–5] There is, however, some uncertainty in the exact value of the current density in Py. If the electron mean free paths in Py and Co were much larger than the thicknesses of the Py and Co layers (which is far from being satisfied at room temperature) and if we could also neglect the specular reflections of the electrons at the interfaces, there would be an uniform current density in the multilayer,[13] that is, for example, 8×10^6 A/cm^2 for 0.6 mA. In the opposite limit of almost independent conduction by the magnetic and nonmagnetic layers (this would correspond to layer thicknesses larger than the mean free paths, or also to almost complete specular reflections at the interfaces, with, in both cases, a vanishing GMR, a straightforward calculation, based on the resistivity of the different metals at room temperature, leads to a current density of 1.75 $\times10^6$ A/cm^2 in Py. 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 real current density in Py is probably in-between, that is of the order of few 10^6 A/cm^2.

Out of the low field range described earlier, the behavior becomes more complex. An example of experimental result is shown in Fig. 3 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 motion direction induced by a positive current at low field. On the other hand, in contrast with the low field behavior, the motion is not reversed for negative currents and the final state is still the AP configuration. For positive fields out of the low field range, the same type of behavior is observed, with a motion towards a more

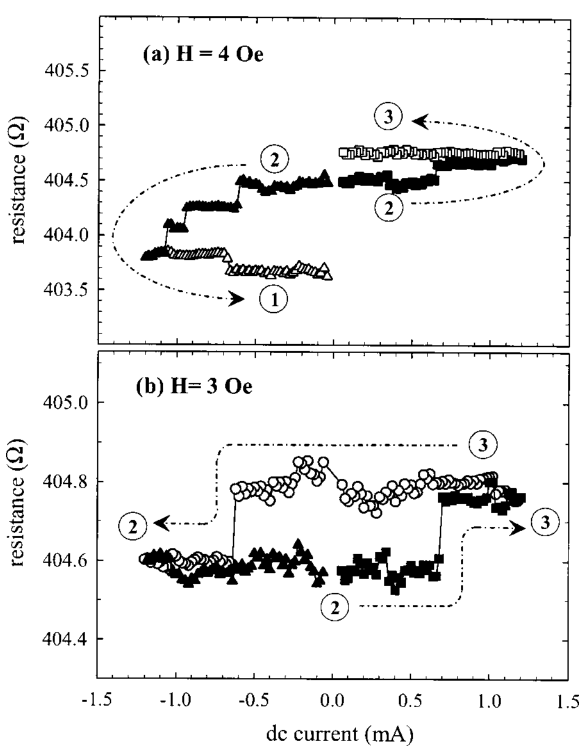

FIG. 2. Resistance vs current in very low constant field H along the stripe. (a) $H=4$ Oe (■—motion from 2 to 3 with a positive current; ▲—motion from 2 to 1 with a negative current); (b) $H=3$ Oe (motion from 2 to 3 with a positive current and back to 2 with a negative current). The numbers 1, 2, and 3 refer to the DW configurations and corresponding resistance levels of Fig. 1. A small contribution $(\sim I^2)$, due to the joule heating $(\Delta T\simeq5$ K), has been subtracted for clarity.

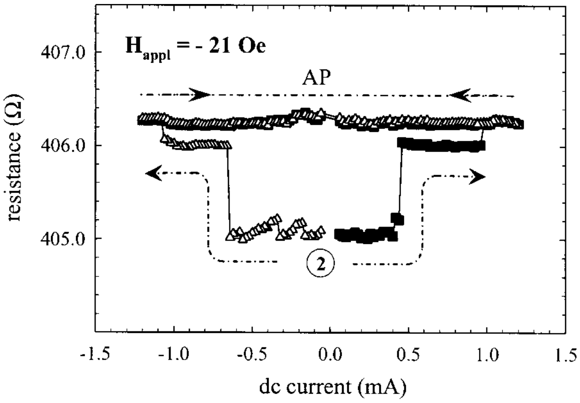

FIG. 3. Resistance vs current for $H = -21$ Oe.

parallel 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 direction. This behavior was also observed in our former experiments[12] with stronger (artificial) pinning centers, where the motion could be obtained only by combining current and applied field.

We will now focus on the interpretation of the DW-drag effects at zero or low field. To start with, we can rule out any contribution from joule heating. From the small quadratic resistance increase with current (the term subtracted in Figs. 2 and 3), the maximum increase of T is about 5 K, and we have checked that, at 300 K, this has practically no effect on the GMR minor loop. An even stronger argument is that heating could not explain that opposite currents produce motions in opposite directions. The oersted field generated by the current ($\leqslant$20 Oe), in a perfect structure, is in the plane of the DW, and it cannot favor a motion in one or in the other direction. In the presence of defects, the oersted field might have a component out of the DW plane, but it can be hardly imagined that different defects give always the same direction for this component and the DW motion. Only the spin transfer mechanism, first proposed by Berger, is consistent with the experimental results at zero or very small field and, particularly, can explain the reversal of the motion with opposite currents. Berger[8] expresses the spin transfer by a torque corresponding to the field $H_B = jP\hbar/e\delta M_s$, perpendicular to the layer. With $M_s = 860\times10^3$ A/m, δ (DW thickness) = 100 nm, P (polarization) = 1, and $j = 5\times10^6$ A/cm^2, we obtain $H_B \simeq 3.8$ Oe, just in the range of the pinning fields of the DW in the Py layer. Although, at the present stage of the theory, the connection between the torque of H_B and the value of the critical current is still unclear, we can conclude that the DW motions at zero or very low field, characterized by a reversal of the motion in opposite currents, can be ascribed to a spin transfer mechanism. On the other hand, the behavior observed at higher fields, with combined influence of current and applied field, is more complex. As suggested by the model of Waintal and Viret,[9] it could be that, in this regime, the depinning of the DW is induced by the distortion of the wall, while the succeeding motion is predominately driven by the field.

In conclusion, we have presented experiments in which a spin valve is switched by current-induced DW motion. In zero or very low field, the DW displacement is in opposite directions for opposite dc currents, and back and forth motions between two pinning centers can be obtained. Our results are consistent with the spin transfer mechanism introduced by Berger.[8] A more complex and unclear behavior is observed when the effect of the current is combined with the effect of an applied field.

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