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Reversible and irreversible current induced domain wall motion in CoFeB based spin valves stripes

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The authors present results on current induced domain wall motion in Co/Cu/CoFeB trilayered stripes. The threshold current densities are around 10^6 A/cm^2 at zero field, i.e., about two orders of magnitude smaller than in single NiFe stripes. The domain wall motion is assisted when the field torque acts in the same direction as the spin torque. When the field torque is opposed to the spin transfer one and above a threshold field, the authors observe a reversible displacement of the domain wall (peak in the dV/dI measurements). This can be ascribed to the onset of domain wall fluctuations, which is confirmed by micromagnetic simulations. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2746952]

Switching a magnetic element without any external field and only with the action of a spin-polarized current has been predicted in early theories by Berger[1] and Slonczewski.[2] In particular, this has been demonstrated in several experiments in which the magnetization is switched through domain wall (hereafter DW) displacement.[3–10] Here, we investigate the current induced domain wall behavior in Co/Cu/CoFeB spin valve stripes. Under the action of the spin transfer torque, a DW is able to propagate in CoFeB for critical current densities as low as 10^6 A/cm^2. This holds promise for high density memory applications, in magnetoresistive random access memories or magnetic race-track memories. Interestingly, when the current and field have opposite effects regarding the DW motion, we observe some unusual features (peaks) in transport measurements that are associated with reversible DW motion over 500 nm. In point contact[11] or nanopillar[12–14] structures, such peaks have been attributed either to current induced telegraph noise[12,13] or to high frequency precessional modes.[15,16] More recently, using real time measurements in DW devices,[17] coherent high frequency precessions have been observed and associated with a periodic modification of the DW structure.[18] We will show that the unusual reversible peaks seen in our measurements can also be attributed to DW fluctuations.

We fabricate 200 nm wide stripes by electron beam lithography and lift-off technique. The magnetic stack (CoO 3 nm/Co 7 nm/Cu 8 nm/CoFeB 4 nm/Au 4 nm) is deposited by dc magnetron sputtering. The Ti/Au electrical pads are deposited by evaporation technique. The Co magnetization is fixed during the experiments and the DW motion is investigated in the soft magnetic CoFeB layer. The stripe has a diamond shape pad to ensure the DW nucleation at low fields [see Fig. 1(a)]. Four probe (A-D for current injection, B-C for voltage measurement) electrical measurements are performed at room temperature, allowing an accurate detection of the DW position through the giant magnetoresistance (GMR) effect.[19] In our convention, a positive current corresponds to electrons flowing from A to D. The resistance versus applied magnetic field curves $R(H)$ (not shown) depict the classical GMR features associated with the complete reversal of the soft CoFeB layer magnetization. We obtain a low (high) resistance level for a parallel (P) [antiparallel (AP)] configuration of the two magnetizations in Co and CoFeB and an intermediate plateau corresponding to an intermediate configuration in which a DW is pinned between the voltage contacts.

This configuration with a pinned DW [between contacts B and C on Fig. 1(a)] is the starting point of our experiments. The magnetic field is then set to 0. For $I>0$, an abrupt decrease of the resistance is observed at $I_C^{\text{down}}=0.2$ mA [see Fig. 1(b)]. For $I<0$, the resistance increases at $I_C^{\text{up}}=-0.8$ mA to an intermediate value, before reaching the AP value at $I_C^{\text{AP}}=-1.1$ mA. This means that the DW moves in opposite directions for opposite current directions. A set of resistance versus current loops has also been recorded for different negative fields H favoring the AP configuration. A field of -1 Oe decreases $|I_C^{\text{up}}|$ by 0.03 mA. As presented in

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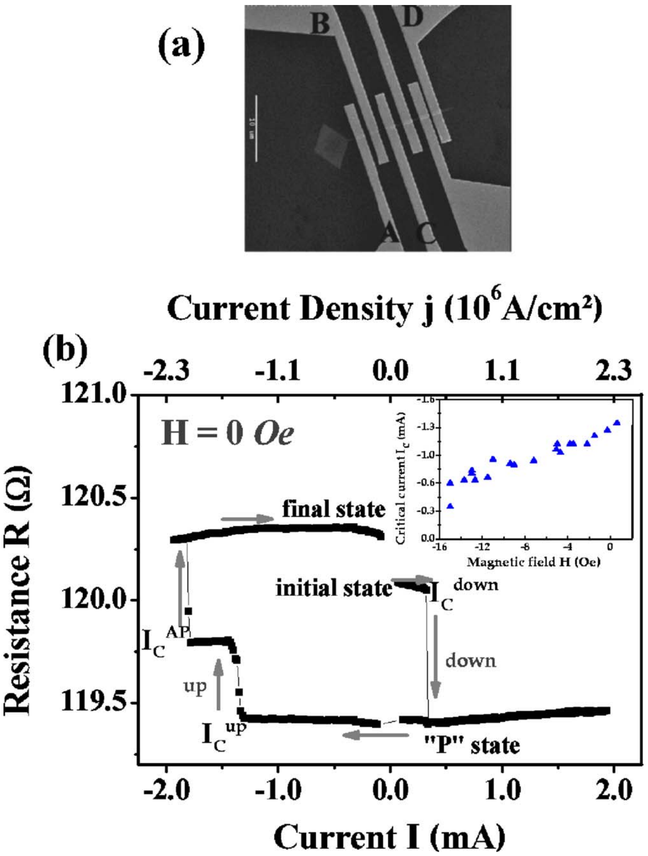

FIG. 1. (Color online) (a) Scanning electron microscopy image of the Co/Cu/CoFeB spin valve stripe (A and D: current pads, B and C: voltage pads) (b) Resistance vs current at $H=0$ Oe. Inset in (b): Critical current vs applied magnetic field.

the inset of Fig. 1(b), smaller values of $|I_C^{\mathrm{up}}|$ are required for smaller values of H (closer to the propagation field at zero current). This can be as well considered as a decrease of the DW propagation fields by injecting current. This behavior can have interesting applications in spintronics devices. Furthermore, the critical current densities at zero field are low: 7×10^6 A/cm^2 for a uniform current distribution in the trilayers. If we now suppose a nonuniform current distribution and take into account the high resistivity of CoFeB, one could estimate the current density in CoFeB to be 6×10^5 A/cm^2. Qualitatively, we can conclude that the required current density is around 10^6 A/cm^2, which is lower by two orders of magnitude than the ones obtained in single NiFe stripes.[6–10] Note that in our spin valve structures, vertical spin currents in the Cu spacer layer generated by the local spin accumulation at the DW position may create a spin transfer torque as in a current-perpendicular-to-plane geometry, thus enhancing the efficiency of the current-in-plane current in CoFeB. This can lower the required current density to move DWs. Similar current densities have also been observed in Co/Pt based spin valve stripes.[20]

We also fabricated spin valve stripes, where the CoFeB layer of the spin valve is substituted by a NiFe layer. A similar behavior is observed, except for the threshold current density at zero field which is around 2×10^7 A/cm^2 (4×10^6A/cm^2) for a uniform (nonuniform) current distribution. The critical densities are higher by a factor of ~3 compared to CoFeB. This difference can be related to a lower Gilbert damping α in CoFeB [$\alpha=0.006$, (Ref. 21)] compared to NiFe [$\alpha=0.02$, (Ref. 18)], since critical currents are proportional to the damping α.[22]

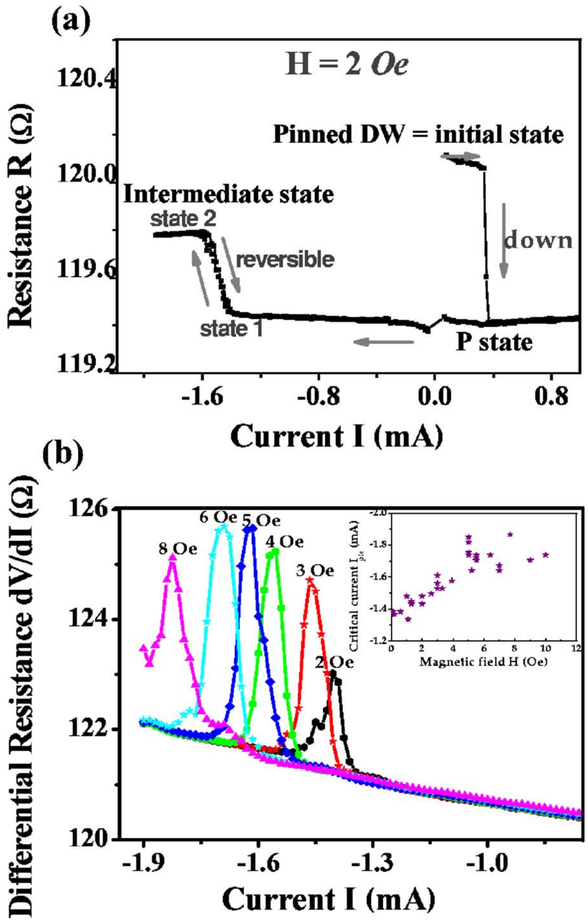

FIG. 2. (Color online) (a) Resistance vs current at $H=+2$ Oe. (b) Differential resistance vs current at different applied magnetic fields. The peaks correspond to reversible upturns of the resistance, as that shown in (a). Inset in (b): Critical current vs applied field.

When the magnetic field and current are both negative and act in the same direction, the DW moves irreversibly. In the case of positive field and negative current, the DW undergoes opposite effects from the current and field. In this situation, we observe a different regime with only a reversible motion of the DW. In fig. 2(a), we present a curve $R(I)$ recorded at $H=+2$ Oe starting from the initial magnetic configuration with the pinned DW state. For $I>0$, we observe an abrupt decrease of the resistance toward the P level, similarly to what was presented before [Fig 1(b)]. We emphasize that the P state corresponds to a situation where the DW has been pushed out the region between the voltage contacts (B and C). The magnetizations in CoFeB and Co are thus parallel. However, the DW is still somewhere in the stripe between the contacts C and D and most likely pinned under one of the contacts (see Fig. 1). From this configuration (labeled state 1 in Fig. 2), for $I<0$, we only observe a reversible increase of the resistance between the P state (state 1) and an intermediate state (state 2). This unusual feature appears for $H>+2$ Oe. To figure out the origin of this reversible behavior, we have measured the differential resistance dV/dI by applying an additional low ac current (20 μA at low frequency of 5 KHz). We detect the presence of a pronounced peak in dV/dI associated with the reversible increase of R. As shown in Fig. 2(b), the onset of the peaks is

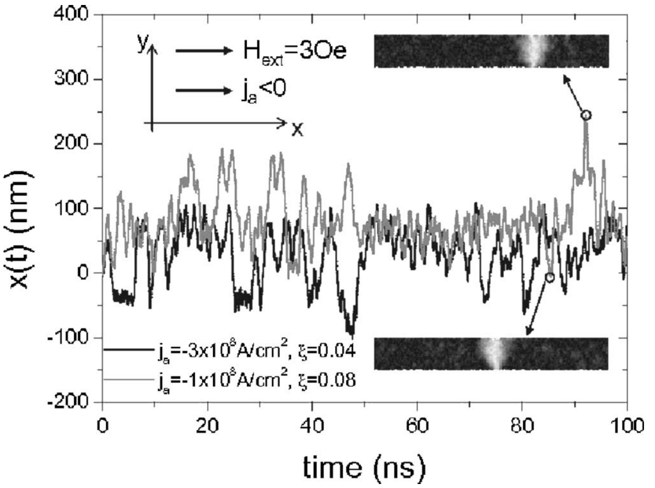

FIG. 3. Oscillations of the DW position as a function of time from simulations for a 200×5 nm^2 NiFe stripe at $H=3$ Oe, for [$j_a=-3\times 10^8$ A/cm^2, $\xi=0.04$] and [$j_a=-1\times 10^8$ A/cm^2, $\xi=0.08$]. The insets depict the micromagnetic configurations in the maximum and minimum values of x for j_a $=-3\times 10^8$ A/cm^2, and $\xi=0.08$.

shifted toward higher currents in absolute values as the magnetic field is increased. In the inset of Fig 2(b), showing the field dependence of the critical currents, we obtain a linear variation with the same slope than in the switching regime [Fig 1(b)]. Note that, for both regimes, the magnetic configuration in which the critical currents are measured is the same state P.

In pillar geometry, this kind of peaks in dV/dI is related to either the onset of stochastic motion of the magnetization (telegraph noise)[12–14] or to high frequency precessional modes of the magnetization.[15,16] Our measurements show that also for DWs, when the current and field have opposite effects, the DW could exhibit a similar stochastic motion between two pinning sites corresponding to the states 1 and 2 [Fig 2(a)]. The peaks should occur when the dwell times in the two states are equal.[13] On the other hand, coherent DW oscillations could also be induced by current and give rise to the peaks. Only time resolved or high frequency measurements would be able to definitively discern these two assumptions.

We have also performed experiments, in which the input parameters are inverted, i.e., at positive current and negative field (not shown). We obtain a reversible decrease of R corresponding to a dip in dV/dI. The field dependence of the dip currents shows that, similar to the case of peaks, they occur at higher currents for higher fields. These observations support our assumption of DW oscillations or telegraph noise induced by spin-polarized dc current.

Similar behavior is also obtained in NiFe based spin valve stripes. The experimental results are not shown here but they exhibit the same reversible DW motion.

In order to get some trends and at least qualitatively understand the nature of the observed dV/dI peaks, micromagnetic simulations have been performed not directly on our systems but for the usual case of NiFe for a semi-infinite stripe. We have used similar dimensions than our stripes, i.e., a width of 200 nm and a thickness of 5 nm. In order to fit more closely the actual sample, a randomly generated lateral roughness has been taken into account. Typical parameters are $M_s=8.6\times 10^5$ A/m, $A=1.3\times 10^{-11}$ J/m, $\alpha=0.02$, and $P=0.4$. The external field pushing the DW toward positive x (see the inset of Fig. 3) is fixed at 3 Oe and several values of the negative current (pushing the DW toward negative x are introduced for two different values of the nonadiabatic parameter $\xi=0.04$ and $\xi=0.08$. As observed in Fig. 3, for $\xi=0.04$ (black line) at $j_a=-3\times 10^8$ A/cm^2, the DW position $x(t)$ fluctuates as a function of time between two positions separated by around 200 nm. The magnitude of the threshold current needed to observe DW oscillations decreases as ξ is increased to 0.08 (gray line) and the DW oscillations amplitude increases to $\sim$250 nm. Although the threshold current is much larger than the experimental one (this discrepancy could be due to the poor knowledge of the exact values of P and ξ), micromagnetic simulations support that the experimental peaks are due to thermally induced DW fluctuations between neighboring pinning sites.

In conclusion, two DW motion regimes have been demonstrated in CoFeB and NiFe based spin valve stripes. In the switching regime, the DW is moved by spin transfer irreversibly. This leads to magnetic switching of the spin valve at very low critical current densities of $\sim 10^6$A/cm^2 (at zero field). In the second regime, reversible DW motions are observed, when the current and field effects are opposite. Micromagnetic simulations indicate that this behavior is related to current induced DW fluctuations.

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