APPLIED PHYSICS LETTERS VOLUME 84, NUMBER 15 12 APRIL 2004

Domain wall displacement induced by subnanosecond pulsed current

C. K. Lim,[a] T. Devolder, and C. Chappert
Institut d'Electronique Fondamentale, UMR 8622, Université Paris Sud, 91405 Orsay Cedex, France

J. Grollier, V. Cros, A. Vaurès, and A. Fert
Unité Mixte de Physique CNRS/THALES, Domaine de Corbeville 91404 Orsay cedex, and Université Paris-Sud, 91405 Orsay Cedex, France

G. Faini
Laboratoire de Photonique et de Nanostructures, LPN-CNRS, route de Nozay, 91460 Marcoussis, France

(Received 17 November 2003; accepted 23 February 2004)

We show that a single current pulse as short as 0.4 ns can trigger domain wall (DW) displacement in spin-valve stripes of 0.3 μm width inserted into a coplanar waveguide. The experiments were carried out with varying current pulse amplitude, duration, polarity, and applied static magnetic field. In zero field, DW displacement occurs in the same direction as the conduction electron current. In finite applied field, the direction of DW displacement is that favored by the field orientation. In both cases, the DW displacement occurs only above a critical current density j_c of the order of 10^6 A/cm^2. The distance traveled by the DW along the stripe increases with the current pulse amplitude and applied field strength, but it does not depend on the pulse duration between 0.4 and 2 ns. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1711168]

Moving a domain wall (DW) can be used to change the magnetic configuration of a magnetoelectronic device, magnetoresistive random access memory, for example, and dragging the DW with an electrical current is a promising mechanism for this motion.[1–3] In the model of Berger,[3] the displacement of the DW is due to spin transfer from the current and arises from a torque exerted by the conduction ($4s$) electron spins on the magnetic moments ($3d$ electrons) through the *sd* exchange interaction. Recently, Waintal and Viret[4] proposed that a second component of the spin torque can arise from the precession of $4s$ electron spins inside the wall. This periodic torque results in a deformation of the DW inner structure.

In the experiments of Grollier *et al.*[5] on current–induced DW motion in spin valves (SV), dc currents were shown to switch the SV back and forth by moving the DW between pinning centers, with a critical current density of the order of 10^6 A/cm^2. A more complex behavior was observed in the presence of an external field. In the context of possible magnetoelectronic applications, the domain wall dynamics resulting from short current pulses is therefore of considerable interest.

Here, we report significant DW displacements triggered by a single subnanosecond current pulse in the free layer (NiFe) of a SV structure. The pulse duration (at half maximum) varies between 0.4 and 2 ns, with 0.32 ns (from 10% to 90%) rise time and 0.66 ns fall time. The pulses were routed in and out of the SV using high bandwidth coplanar waveguide accesses, as shown in Fig. 1. The SV (CoO_3/Co7/Cu10/NiFe5/Au3, where a number indicates the thickness in nm) stripe was 50 μm long while the sensed length was 30 μm long with a width of 0.3 μm, very similar to that considered in Ref. 5. The shorter sensed length was due to the overlap of the electrical contacts shunting the current away from the ends of the stripe. A large square pad (1×1 μm^2) at one end of the stripe ensures the reproducibility of DW injection.[6] A notch located at one-third of the stripe length was patterned to pin the DW.[7,8]

The SV stripe was first saturated in large negative field (point A, Fig. 2) to obtain a parallel state for the NiFe and Co magnetizations (lowest resistance state). The external field was then swept slowly (1 Oe/s) to nucleate a DW inside the pad and the sweeping was continued until the DW reached the notch where it became pinned (point B, Fig. 2). This is seen as a step at 22–25 Oe in the giant magnetoresistance loop (point B), at which one third of the length of the NiFe layer has been switched antiparallel to the Co layer, thus creating a head-to-head DW. At point B, the cycling was stopped and the field was switched off. We waited 1 min for the magnetic configuration to stabilize before applying the current pulse. Resistance changes were measured at 1 s intervals by a small ac voltage of 0.1 V (peak to peak) through the same SV stripe via a bias tee, with noise level <0.2 Ω (so-called aftereffect measurement). The sample was then systematically resaturated to point A before starting another measurement. The shift of the minor loop in Fig. 2 is not due to interlayer coupling but is rather the consequence of imper-

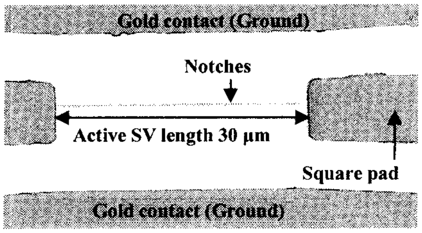

FIG. 1. Scanning electron micrograph showing the spin valve stripe with a square pad at one end, inserted in a coplanar waveguide.

---

[a] Author to whom correspondence should be addressed; electronic mail: chee.lim@samsung.com

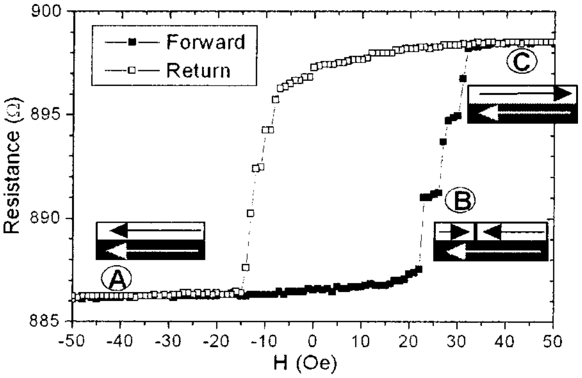

FIG. 2. Minor hysteresis loop of the spin valve stripe. A step is seen at field 25 Oe, point B.

fect saturation of the NiFe layer at point C, where end domains may be present in the nonsensed part of the SV stripe.

First, DW displacement was studied as a function of current pulse amplitude for durations of 0.4, 0.5, 0.8, 1, and 2 ns with no external field. Figure 3(a) shows the change in resistance measured as a function of the current pulse amplitude for a 0.4 ns pulse in positive or negative direction, denoted by I^+ or I^-. The magnetization directions in the NiFe and Co layers and the directions of I^+ and I^- are shown schematically in Fig. 3(a) I^+ and I^- refer to the charge current (the electrons flow in the opposite direction).

With a trapped DW (point B), applied current pulses with increasing I^+ do not change the resistance until I^+ reach a critical value $I_c^+ \approx 0.5$ mA. For this current amplitude, the SV resistance increases sharply to point C (antiparallel state). The corresponding motion of the DW is opposite to the direction of the charge current. The critical positive current of 0.5 mA represents a current density j_c of 6.7×10^6 A/cm^2, assuming a uniform current in the sample. This value is strictly speaking the possible upper value of the current density in the NiFe layer in the limit where the electron mean free paths in Cu, NiFe, and Co are supposed to be much larger than the thicknesses of the Cu, NiFe, and Co layers. This condition is far from being satisfied, so that the real current density in Co is certainly smaller.

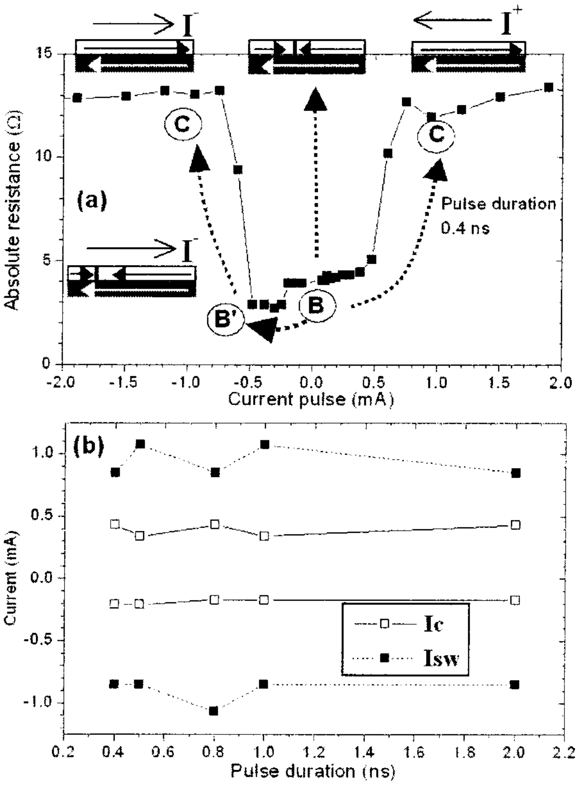

FIG. 3. (a) Resistance vs current pulse amplitude for a current pulse of 0.4 ns duration. (b) Plots of the minimum current generating DW motion I_c (open squares) and the current triggering the complete switching I_{SW} (filled squares) vs pulse duration from 0.4 to 2 ns.

A similar behavior was observed for opposite current polarity in the low current limit. At low negative current amplitude, the SV resistance decreases to point B′ for $|I^-| > 0.2$ mA. This gives the critical negative current $I_c^- \approx -0.2$ mA above which the current succeeds in efficiently pulling the DW towards the parallel state of the SV. The DW displacement was estimated to be 2 μm. The equivalent maximum current density is 2.7×10^6 A/cm^2. Hence, we find that an opposite current displaces the DW in the opposite direction, in agreement with the spin transfer mechanism. However, it is important to note that the SV was not switched to the parallel state completely at point B′, $I^- \approx -0.4$ mA and the DW remains at an intermediate pining center.

Surprisingly, further increases in I^- led to a resistance increase immediately at point C, which corresponds to an antiparallel state of the SV, which appears as if the DW motion were reversed. This unexpected behavior was highly reproducible for all current pulse durations and on different SV stripes. Complete switching towards antiparallel state (point C) was achieved with current pulses, I_{sw}, of ± 0.6 mA, which is equivalent to a switching current density j_{sw} of 8×10^6 A/cm^2.

Another surprising observation is shown in Fig. 3(b), where I_c and I_{sw} are shown as a function of pulse duration. It is experimentally unambiguous that I_c^- and I_c^+ are independent of the current pulse durations. This is a very important result in our experiment as it contradicts the spin transfer model, which we will discuss further next. The difference in the positive and negative critical currents, $I_c^- < I_c^+$, is perhaps due to the small Néel coupling of 1 Oe present in our samples which favors a parallel alignment, and hence, smaller negative currents are required to move the wall towards a more parallel configuration.

Figure 4 shows the displacement observed with an external constant field of ± 2 Oe (along the long axis) and for a 1 ns current pulse. We observe that once the critical current thresholds $I_c \approx +0.3$ and -0.4 mA have been exceeded, the DW always moves in the direction defined by the external field and is independent of the current direction. A positive field H^+ moves the wall towards the antiparallel alignment (high resistance) of the NiFe and Co layers, from point B to point C, while a negative field H^- favors the parallel state (low resistance), from point B to point A. Switching with an applied field of only 2 Oe means that the switching field H_{sw} of the SV has been greatly reduced by the pulse (nearly by a factor of 10). This looks like a reduction of the coercivity of the SV. The value of j_{sw} has also decreased to 6.7×10^6 A/cm^2. Table I shows the value of j_{sw} measured at four different applied fields. The current density required to switch the SV decreases rapidly with applied field.

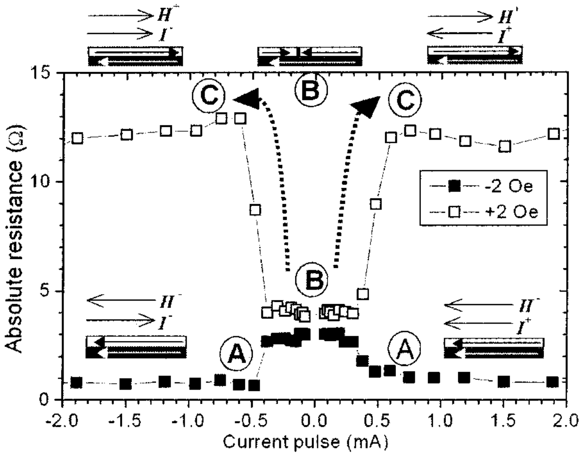

FIG. 4. Resistance vs current pulse amplitude for constant applied fields, ±2 Oe. Pulse duration was 1 ns.

The four important outcomes from our experiments are as follows.

First, the direction of DW displacement is found to be opposite to the current direction (and so in the direction of the electron flow) at low current densities [point B to C for I^+ and point B to B′ for I^- in Fig. 3(a)]. The critical density for both current directions is of the order of 10^6 A/cm^2, which is consistent with the spin transfer model and other dc experiments.[5] These are convincing signatures of the spin transfer mechanism. However, this behavior is observed only in the small field limit.

Second, the DW displacement induced by current pulses is independent of the pulse duration up to 2 ns. Berger[9] has developed a spin transfer model for DW displacement by current pulse with a small rise time (<20 ns for NiFe film) and a very long fall time. The sudden variation from the short rise time leads to a DW launch velocity. This motion is then damped by dissipative processes during the long fall time of the pulse. With the subnanosecond pulses considered, the effect of DW pinning and damping should be negligible in our experiment during both the rise and fall time of the pulse. This implies that a stepwise change in DW velocity during the rise time must be accompanied by a similar stepwise change during the fall time, according to Eq. (8) in Ref. 9. Thus, the total DW displacement should scale with the duration of the current pulse, which is contrary to our results. For an alternative explanation we can consider the DW inertia,[10] which allows the DW to move after the pulse. However, the observed displacement of 20 μm appears too high for pure inertial motion.

TABLE I. Measured current density $j_{\rm sw}$ permitting a complete switching, and dependence with the applied field.

$H_{\rm ext}$ (Oe)	$j_{\rm sw}$ (10^{-6} A/cm^2)
±2	6.7
±3	5.3
±7	4.2
±12	2.6

Our third observation is the increase in resistance from point B′ to C for I^- in Fig. 3(a), that is a surprising reversal of the motion above some threshold current. We can rule out the effect of Joule heating at this current density since the heating from such a short current pulse is negligible in our experiments, with $\Delta T < 1$ K.

The fourth observation is the complex behavior of DW displacement in the presence of both external field and pulse current. The direction of DW displacement is determined solely by the external field. We have managed to switch the SV with a 2 Oe field combined with a pulse current of 6.7 $\times 10^6$ A/cm^2. The switching field of the SV has been reduced by a factor of 10. We believe that this is not due to the effect of spin accumulation on the DW width. Spin accumulation tends to increase the width of the DW and hence reduces the pinning field of the DW. However, spin accumulation is only important in the case of a narrow DW and it is negligible for our SV stripe, for which the wall width is likely to be greater than 100 nm. In light of the recent calculation of Waintal and Viret,[4] one may argue that distortions in the wall profile caused by the current can lead to wall depinning. In this case, the effect of the current is simply to depin the wall and its subsequent motion could be governed entirely by the magnetic field.

In conclusion, we have demonstrated that switching in SV by current pulse-induced DW displacement is possible with pulses as short as 0.4 ns. The displacement is independent of the pulse duration from 0.4 to 2 ns. The direction of the DW displacement depends on the conduction electron flow in the absence of an external field, bearing the clear signature of spin transfer mechanism. The behavior becomes more complicated when an external field is applied.

C.K.L. acknowledges the financial support provided through the European Community's Human Potential Program under Contract No. HPRN-CT-2002-00318 (ULTRASWITCH). This work was also supported through MRT project "Magmem II" (01V0030) and the ACI Contract No. "BASIC" (27-01).

[1] G. A. Prinz, J. Magn. Magn. Mater. **200**, 57 (1999).
[2] D. A. Allwood, G. Xiong, M. D. Cooke, C. C. Faulkner, D. Atkinson, N. Vernier, and R. P. Cowburn, Science **296**, 2003 (2002).
[3] L. Berger, J. Appl. Phys. **55**, 1954 (1984).
[4] X. Waintal and M. Viret, Cond-mat/0301293, 2003.
[5] J. Grollier, D. Lacour, V. Cros, A. Hamzic, A. Vaurès, A. Fert, D. Adam, and G. Faini, J. Appl. Phys. **92**, 4825 (2002); J. Grollier, P. Boulenc, V. Cros, A. Hamzic, A. Vaurès, and A. Fert, Appl. Phys. Lett. **83**, 509 (2003).
[6] K. Shigeto, T. Shinjo, and T. Ono, Appl. Phys. Lett. **75**, 2815 (1999).
[7] T. Ono, H. Miyajima, K. Shigeto, K. Mibu, N. Hosoito, and T. Shinjo, J. Appl. Phys. **85**, 6181 (1999).
[8] A. Himeno, T. Ono, S. Nasu, K. Shigeto, K. Mibu, and T. Shinjo, J. Appl. Phys. **93**, 8430 (2003).
[9] L. Berger, J. Appl. Phys. **71**, 2721 (1992).
[10] L. Lopez-Diaz, M. Klaui, J. Rothman, and J. A. C. Bland, J. Magn. Magn. Mater. **242**, 553 (2002).