

Spin-transfer-induced magnetic domain formation

T. Yang^{a)} and A. Hirohata

Frontier Research System, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

T. Kimura and Y. Otani

Institute for Solid State Physics, University of Tokyo, Kashiwa, Chiba 277-8581, Japan
and Frontier Research System, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

(Received 13 May 2006; accepted 29 July 2006; published online 5 October 2006)

A special nanopillar comprised of a thick top ferromagnetic layer and a thin bottom ferromagnetic layer is fabricated and the transport properties are measured by applying a dc current and an external field. It is shown experimentally that the dc current flowing through the nanopillar could lead to intermediate states between the antiparallel and the parallel magnetic configurations. The intermediate states are characterized to be the result of domain formation in the bottom ferromagnetic layer, due to the injection of spin-polarized current. The results verify that the spin-transfer effect may induce domain formation in a magnetic thin film. It is also suggested that when the spin-transfer effect is utilized to switch the nanopillar device, the domain formation may result in the incomplete magnetization switching. © 2006 American Institute of Physics.

[DOI: 10.1063/1.2357002]

I. INTRODUCTION

It has been theoretically predicted^{1,2} and experimentally³⁻⁸ verified that spin injection induces magnetization switching. When a spin-polarized current traverses a thin nanomagnet, the spin angular momentum transfer exerts a torque on the local magnetic moment, resulting in the magnetization switching or the spin wave excitation. This effect is important not only for the fundamental interests but also for the practical application. Most of the experimental studies have been carried out with a nanopillar structure having a bottom ferromagnetic layer and a top nanomagnet. The magnetization switching of the top nanomagnet has been extensively investigated. However, little attention has been paid on the influence of the spin-transfer effect on the bottom ferromagnetic layer in the nanopillar. Nevertheless, intermediate states^{3,9} have been reported during the spin-transfer-induced magnetization switching and attributed to the domain formation in the bottom ferromagnetic layer.⁹ The intermediate state means the incomplete magnetization switching, possibly influencing the performance of the nanopillar device. On the other hand, unlike the spin-transfer-induced magnetization switching of a nanomagnet, there are few studies on the domain formation induced by the spin-transfer effect when a spin-polarized current is perpendicularly injected into a magnetic thin film. Only the domain formation induced by the injection of an unpolarized current through a point contact has been reported and ascribed to the spin-transfer effect.^{10,11}

In this work, we further verify the spin-transfer-induced domain formation by injecting a spin-polarized current perpendicularly into a magnetic film. At the same time, the influence of the domain formation on the switching behavior of a nanopillar is also investigated. For the purposes of this study, we fabricated a nanopillar with a structure, as sketched

in Fig. 1(a) (hereafter structure A), comprised of a thick Co top nanomagnet layer and a thin Co bottom layer, which is extended horizontally. When a dc current is injected into the structure, the thick top layer is expected to be magnetically fixed and serve as the polarizer to produce the spin-polarized current. With this special structure, the effect of the spin-polarized current on the bottom magnetic thin film is studied. As a comparison, a nanopillar with the structure shown in Fig. 1(b) (hereafter structure B) is also fabricated, which differs from structure A only in that both the top and the bottom Co layers are patterned into nanomagnets. The thickness of each layer in both nanopillars is shown in the figures.

II. EXPERIMENTAL RESULTS AND DISCUSSIONS

The nanopillars are fabricated from the electron-beam-evaporated multilayers by electron-beam lithography, ion milling, and photolithography. The transport properties are measured by a lock-in technique at room temperature by applying an external field along the easy axis of the nanopillar. Both nanopillars are fabricated in the same shape and size, i.e., $140 \times 70 \text{ nm}^2$.

We firstly checked the magnetization switching induced by the external field for both structures B and A. As can be seen from Figs. 2(a) and 2(b), when the external field is

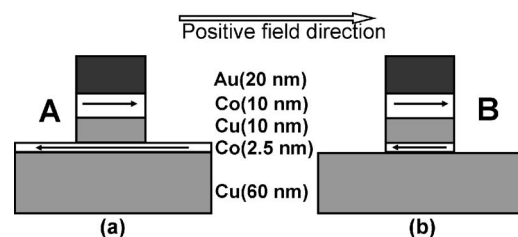


FIG. 1. (a) The nanopillar structure studied in this work and (b) the structure as a comparison. The arrows in (a) and (b) represent the direction of the magnetization.

^{a)}Electronic mail: tyang@riken.jp

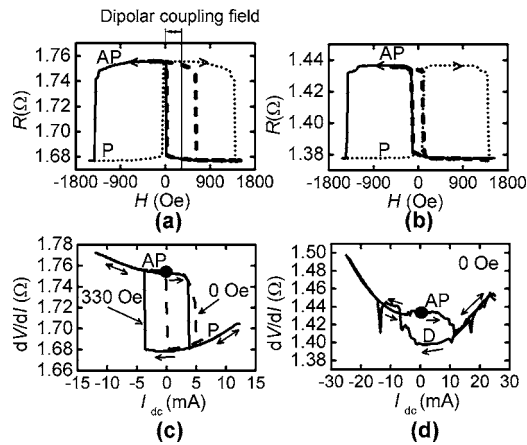


FIG. 2. MR and $dV/dI \sim I_{dc}$ loops for nanopillars with structure B [(a) and (c)] and structure A [(b) and (d)], respectively. The arrows represent the sweeping direction of the external field or the dc current. The dashed lines in (a) and (b) are the minor loops. In (a) and (b), the solid lines are obtained with sweeping the field from the positive to the negative while the dotted lines are obtained with the opposite sweeping direction. The solid line and the dashed line in (c) are measured under external fields 330 and 0 Oe, respectively. The solid circles in all the figures indicate the point where the measurement starts.

swept between +1500 and -1500 Oe, two resistance states can be observed in both magnetoresistance (MR) loops, corresponding to the parallel (P) and the antiparallel (AP) magnetic configurations between the two Co layers, respectively. For either A or B structure, the P-to-AP magnetization switching occurs at small fields, caused by the switching of the bottom Co layer. On the other hand, the AP-to-P magnetization switching occurs at high fields, caused by the switching of the top Co nanomagnet. The difference between the two loops is that the P-to-AP magnetization switching occurs before the field is reversed for structure B [Fig. 2(a)], while it occurs after the field is reversed for structure A [Fig. 2(b)]. Such a difference implies the presence of the antiferromagnetic dipolar coupling between the two Co layers in structure B, originating from the magnetic charges around the side edges of both Co layers. The minor loops for the bottom Co layers are also plotted in the figures with dashed lines. According to the shift of the minor loop center from the zero field in Fig. 2(a), the dipolar coupling field is determined to be 330 Oe. On the other hand, the minor loop in Fig. 2(b) is not shifted. This is because the bottom Co layer is a continuous thin film, thus the stray field of the top Co layer does not affect its switching behaviors.

To study the influence of the spin transfer on the bottom layer, a dc current I_{dc} is injected into each structure, which is preset to be the AP state with the top Co layer magnetization in the positive field direction and the bottom Co layer magnetization in the negative field direction, as illustrated in Figs. 1(a) and 1(b). In our measurement the positive dc current is defined as flowing from the bottom to the top of the pillar. The differential resistance dV/dI is measured with sweeping the dc current from 0 mA to the positive maximum, then to the negative maximum, and finally back to 0 mA. For both structures, hysteresis loops are observed in the $dV/dI \sim I_{dc}$ curves shown in Figs. 2(c) and 2(d), respectively. However, the full magnetization switches between AP

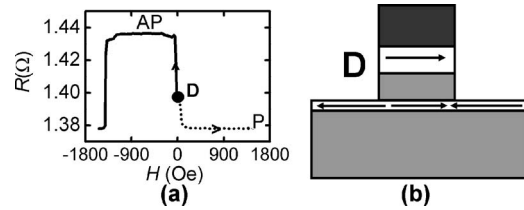


FIG. 3. (a) The resistance dependence on the external field and (b) the magnetic configuration for the D state.

and P states are realized only for structure B. In Fig. 2(c), the AP state for structure B is switched to the P state when the dc current is increased in the positive direction, while the P state is switched to the AP state when the dc current is swept from the positive maximum to the negative maximum. This is opposite to the case of the conventional nanopillar,^{3,9} implying that the bottom nanomagnet is completely reversed by the spin-polarized current. Remarkable is that the dc current cannot realize a full switching between P and AP states for structure A. As plotted in Fig. 2(d), when the dc current is increased from 0 mA without the external field, the AP state gradually evolves into another state, which is retained when the dc current is further increased to +25 mA and then decreased to 0 mA again. According to the resistance value at 0 mA, this state (hereafter D state) is an intermediate (IM) state between AP and P states. As the dc current is increased in the negative direction, the D state switches back to the AP state, which is retained when the dc current is decreased back to 0 mA.

To characterize the D state, the effect of the external field on it is investigated without the dc current. As can be seen from the evolution of the resistance with the external field [Fig. 3(a)], the D state is switched to the P state when the field is increased to 100 Oe, coincident with the switching field of the bottom Co layer shown in Fig. 2(b). On the other hand, the D state is transformed to the AP state when the field is increased in the negative direction. With further increasing the negative field, the AP state finally switches to the P state at -1400 Oe, the same value as the switching field of the top nanomagnet shown in Fig. 2(b). The results can only be explained with the magnetic configuration sketched in Fig. 3(b), i.e., a domain in the bottom Co layer for the D state. For such a magnetic configuration, a positive field exceeding 100 Oe aligns the whole bottom layer in the positive field direction, leading to the P state. On the other hand, a small negative field reverses the domain, resulting in the AP state. The AP state is further switched to the P state when the negative field is large enough to switch the top nanomagnet.

The formation of the domain can be explained as follows. When the positive dc current is applied to the AP state of structure A, the conduction electrons flow from the top to the bottom. When passing through the thick top layer, the electrons are spin polarized. Through the spin-transfer effect, these spin-polarized electrons exert a torque on the magnetization of the bottom Co layer when flowing into it. The spin torque tends to align the magnetization of the bottom Co layer to be parallel to the magnetization of the top Co layer, finally forming a reversed domain in the bottom Co layer. This domain keeps stable even when the dc current is re-

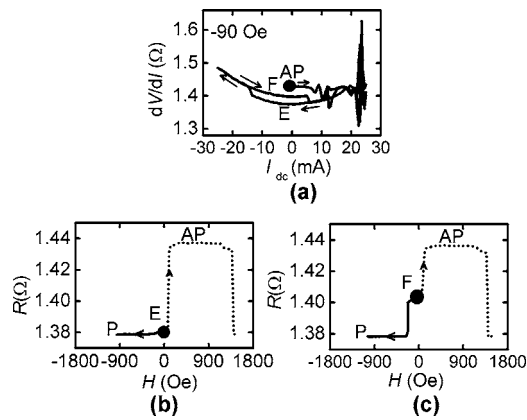


FIG. 4. (a) dV/dI dependence on I_{dc} for the nanopillar with structure A at the external field of -90 Oe. The arrows represent the sweeping direction of the external field or the dc current. (b) and (c) are the resistance dependences on the external field for states E and F, respectively.

duced to 0 mA. When the dc current is applied in the negative directions, the electrons flow from the bottom to the top. Those electrons with spin opposite to the major spin in the top layer are reflected back into the bottom Co layer and again exert a spin torque on the bottom Co layer, i.e., on the domain. This spin torque tends to align the magnetization of the domain to be antiparallel to the top layer. Therefore, as the dc current is increased in the negative direction, the domain is switched and hence disappears, back to the AP state again.

The above experimental results and discussions show that when a spin-polarized current is injected perpendicularly into a thin film, a domain can be formed through the spin-transfer effect. This domain is even stable when both the field and the dc current are removed. The domain formation results in an IM state in the nanopillar with structure A.

The $dV/dI \sim I_{dc}$ measurement is also performed under various negative external fields for structure A. All the measurements start from the AP state shown in Fig. 1(a). The dc current is swept in the sequence of $0 \rightarrow 25 \rightarrow 0 \rightarrow -25 \rightarrow 0 \rightarrow 25$ mA. The result measured at the field of -90 Oe is depicted in Fig. 4(a), much different from the one measured at zero field. During the first sweeping from 0 to 25 mA, the resistance starts to fluctuate at about 6 mA. When the dc current is swept back from 25 to 0 mA, the resistance is stabilized at the value for the P state. This parallel state is denoted as E state hereafter. With further sweeping the dc current from 0 to -25 mA, the E state switches to another IM state at -15 mA. We denote this IM state as F state, which remains stable when the dc current is swept back to 0 mA from -25 mA.

To clarify the switching behaviors, both E and F states are characterized by investigating the resistance evolution with the external field at zero dc current. The results for E and F states are plotted in Figs. 4(b) and 4(c), respectively. According to Fig. 4(b), increasing the field in the positive direction firstly switches the E state to the AP state at about 100 Oe and then the AP state is switched to the P state at about 1400 Oe. When the field is increased in the negative direction, no state transition can be observed. The results suggest that the E state is a parallel state with both Co layers

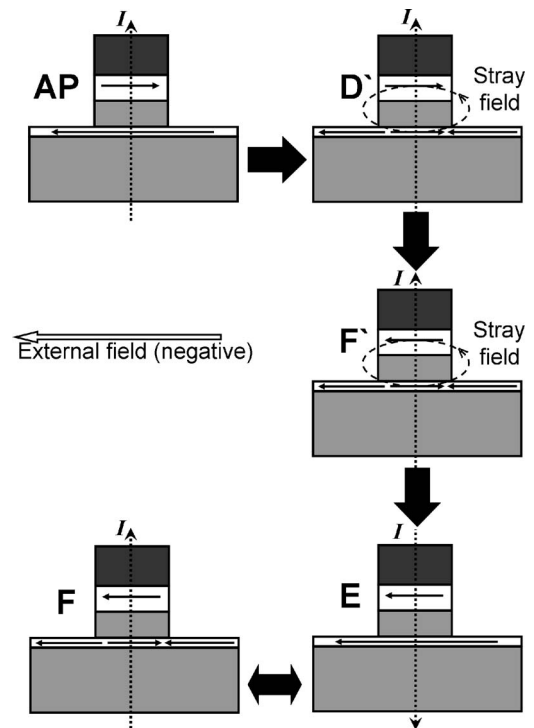


FIG. 5. The evolution of the magnetic configuration corresponding to Fig. 4(a).

aligned in the negative field direction, as shown in Fig. 5. On the other hand, the F state transforms to the AP (or P) state as the field is increased in the positive (or negative) direction [Fig. 4(c)]. The transition to the AP state occurs at a field equal to the switching field of the bottom Co layer. With further increasing the positive field, the AP state is switched to the P state at the switching field of the top nanomagnet. The deduced magnetic configuration for F state differs from the E state in that a reversed domain is formed in the bottom Co layer, as also shown in Fig. 5.

Since the E state is developed from the AP state shown in both Figs. 1(a) and 5 during the $0 \rightarrow 25 \rightarrow 0$ mA sweeping, it seems that a positive dc current switches the magnetization of the top nanomagnet to be parallel to the magnetization of the bottom Co layer. But according to the spin-transfer theory, the spin torque exerted on the top nanomagnet favors an antiparallel configuration when the dc current is positive, contradictory to the present result. The possible mechanism for this abnormal magnetization switching of the top nanomagnet is as follows. As discussed previously, a domain is firstly nucleated in the bottom Co layer as the dc current is increased in the positive direction for the AP state. Thus a magnetic configuration similar to the D state is resulted. We denote it as D' state, as depicted in Fig. 5. Once the reversed domain is formed in the bottom Co layer, the spin torque exerted on the top layer is also reversed, facilitating the magnetization reversal of the top nanomagnet. At the same time, the stray field from the domain wall also attempts to reverse the top layer.¹² Finally, assisted by the negative external field, the top layer is reversed, producing the F' state in Fig. 5. As soon as the top layer is reversed, the spin torque on the bottom Co layer, favoring a parallel configuration between the top and the bottom Co layers, reverses the domain with

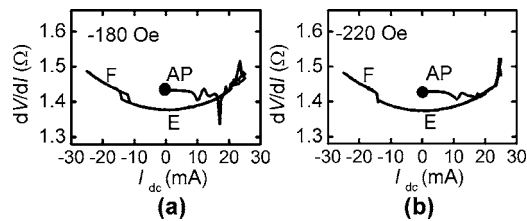


FIG. 6. dV/dI dependences on I_{dc} for the nanopyllar with structure A at the external fields of (a) -180 Oe and (b) -220 Oe, respectively.

the help of the external field. Therefore the domain is annihilated, resulting in the E state. Under the -90 Oe external field and the positive dc current, the D' and F' states seem not to be stable, but only transition states in the switching process occurring during the $0 \rightarrow 25 \rightarrow 0$ mA sweeping.

The domain formation induced when the E state switches to the F state should be attributed to the spin torque exerted by the electrons reflected back to the bottom Co layer. During the sweeping from -25 to 25 mA, the spin torque stabilizing the domain structure decreases. Finally, at a positive dc current of 5 mA, the domain is annihilated by the external field as well as the spin torque, which changes its direction as the dc current becomes positive. Hence the F state is switched back to the E state, as shown in Fig. 4(a).

Figure 5 illustrates the whole switching process when the dc current is swept in the sequence of $0 \rightarrow 25 \rightarrow 0 \rightarrow -25 \rightarrow 0 \rightarrow 25$ mA under a field of -90 Oe.

As shown in Figs. 6(a) and 6(b), the hysteresis loop appearing in Fig. 4(a) shrinks under an increased negative field, due to the earlier switching from the F state to the E state. The hysteresis finally disappears at the field of -220 Oe. On the other hand, the switching current from the E state to the F state is almost independent of the external field. Such a field dependence of switching current is similar to that for the conventional-type nanopyllar, attributed to the thermal effect.¹³

At last, we discuss how the domain can be stabilized in the bottom Co layer of structure A. Although the bottom layer is designed to be very thin, the domain wall energy

always appears when a reversed domain is formed, destabilizing the domain. However, considering the ion milling during the fabrication process, we believe that the defects caused by the ion irradiation as well as other natural defects provide pinning sites to the domain wall and hence stabilize the domain.

III. SUMMARY

In summary, it is shown that the perpendicular injection of a spin-polarized current into a magnetic thin film can induce the domain formation through the spin-transfer effect. The domain formation may result in the incomplete switching and thus negative influences on the performance of the nanopyllar device. We also explained an abnormal switching of the top nanomagnet observed when the dc current is injected.

ACKNOWLEDGMENTS

We are grateful to Dr. Tsukagoshi and the Nanoscience Development and Support Team of RIKEN for their great supports.

- ¹J. C. Slonczewski, *J. Magn. Magn. Mater.* **159**, L1 (1996).
- ²L. Berger, *Phys. Rev. B* **54**, 9353 (1996).
- ³J. A. Katine, F. J. Albert, R. A. Buhrman, E. B. Myers, and D. C. Ralph, *Phys. Rev. Lett.* **84**, 3149 (2000).
- ⁴J. Grollier, V. Cros, A. Hamzic, J. M. George, H. Jaffre's, A. Fert, G. Faini, J. Ben Youssef, and H. Legall, *Appl. Phys. Lett.* **78**, 3663 (2001).
- ⁵J. Z. Sun, D. J. Monsma, D. W. Abraham, M. J. Rooks, and R. H. Koch, *Appl. Phys. Lett.* **81**, 2202 (2002).
- ⁶S. Urazhdin, N. O. Birge, W. P. Pratt, Jr., and J. Bass, *Phys. Rev. Lett.* **91**, 146803 (2003).
- ⁷F. J. Albert, N. C. Emley, E. B. Myers, D. C. Ralph, and R. A. Buhrman, *Phys. Rev. Lett.* **89**, 226802 (2002).
- ⁸Y. Jiang, T. Nozaki, S. Abe, T. Ochiai, A. Hirohata, N. Tezuka, and K. Inomata, *Nat. Mater.* **3**, 361 (2004).
- ⁹T. Yang, T. Kimura, and Y. Otani, *J. Appl. Phys.* **97**, 064304 (2005).
- ¹⁰T. Y. Chen, Y. Ji, C. L. Chien, and M. D. Stiles, *Phys. Rev. Lett.* **93**, 026601 (2004).
- ¹¹E. B. Myers, D. C. Ralph, J. A. Katine, R. N. Louie, and R. A. Buhrman, *Science* **285**, 867 (1999).
- ¹²M. R. McCartney, R. E. Dunin-Borkowski, M. R. Scheinfein, D. J. Smith, S. Gider, and S. S. P. Parkin, *Science* **286**, 1337 (1999).
- ¹³D. Lacour, J. A. Katine, N. Smith, M. J. Carey, and J. R. Childress, *Appl. Phys. Lett.* **85**, 4681 (2004).