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Spin transfer in nanomagnetic devices with perpendicular anisotropy

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Spin momentum transfer in a nanomagnetic device with perpendicular magnetic anisotropy for both free and fixed magnetic layers is studied. The perpendicular anisotropy is induced by using CoFe/Pt multilayer. The magnetoresistive loop shows that the perpendicular switching fields for the free and fixed layers are 170 and 380 Oe, respectively, with $\Delta R/R = 0.47\%$. Resistance-current scanning clearly shows a full out-of-plane switching of the free layer magnetization under a sweeping current, which fully excludes the effect of switching by the magnetic field generated by the current. The critical current density is around 1.0×10^8 A/cm^2, which could be tuned by changing the CoFe/Pt multilayer structures. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2198797]

Spin transfer predicted by Slonczewski[1] and Berger[2] has attracted a great deal of attention in recent years. Up to now, all spin transfer related reports concentrate on magnetic films or devices with in-plane anisotropy.[3–23] In this work, we report the spin momentum transfer study in a nanomagnetic device with perpendicular magnetic anisotropy for both free and fixed magnetic layers. In comparison with those with in-plane anisotropy, spintronic devices with perpendicular magnetocrystalline anisotropy not only can satisfy the thermal stability requirement but also have no limit of cell aspect ratio, which shows an advantage of scaling for high packing density: one of the key challenges for future magnetic random access memory (MRAM) application.[24–28] Although the spin dynamics for the magnetic moment perpendicular to the plane has been reported,[21,29] the perpendicular moment requires a large applied magnetic field ($>4\pi M_s$), which always forces the free layer towards to a fixed direction. Thus, the spin transfer behavior will be asymmetric and much different from that in a device with perpendicular anisotropy. Also the spin transfer behavior in a device with perpendicular anisotropy should provide a good platform for investigating the physics of spin transfer process in the future.

In order to introduce the perpendicular anisotropy, $[Co_{90}Fe_{10}/Pt]_n$ multilayers were used as the free layer and fixed layer in the spin valve (SV) structures. By adjusting the CoFe/Pt bilayer thickness, the anisotropy of the multilayer could be controlled to be either in plane or perpendicular to plane.[25,26] In addition, different CoFe/Pt thickness ratios could result in different coercivities, by which the switching fields of the fixed layer and the free layer could be distinguished. To investigate the spin transfer properties of a nanomagnetic device with perpendicular anisotropy, three kinds of devices with different free layer structures were studied in this work. Structure I has the film structure as Si/SiO$_2$/bottom electrode/[CoFe2.5 Å/Pt15 Å]$_5$/CoFe5 Å/Cu30 Å/[CoFe4.5 Å/Pt23 Å]$_7$/top electrode. The space layer Cu is sandwiched by two CoFe layers instead of Pt layer. This enhances the spin polarization and thus the magnetoresistance ratio (MR). The fixed layer part has [CoFe4.5 Å/Pt23 Å] 7 cycles, while the free layer part [CoFe2.5 Å/Pt15 Å] has only 5 cycles. Such a design enlarges the switching field gap between the free and fixed layers in the MR and spin transfer testing. The perpendicular magnetic properties of the sheet film with the structure I were measured by a vibrating-sample magnetometer (VSM) with applied field perpendicular to the film plane, as shown in Fig. 1. The square loop shape ($M_r/M_s=1$) indicates that the easy axis of the free layer and fixed layer is out of plane. Furthermore, the sharp two-step switching clearly shows that the free layer and fixed layer were well separated. The switching fields for the free layer (H_{free}) and the fixed layer (H_{fix}) are around 170 and 380 Oe, respectively. The gap between H_{free} and H_{fix} is around 200 Oe. The flat stage between the two switching points indicates that the free layer could be operated in a relatively wide field range without influencing the fixed layer magnetization status. This provides a solid base for the spin transfer testing at the device level, which will be discussed in the next two paragraphs.

The area of the nanomagnetic device in this work is 180×250 nm^2 with a slight elliptical shape patterned by an advanced phase-shift mask technique. The detailed device fabrication process can be found in our previous reports.[30,31] Figure 2(a) shows the current-perpendicular-to-plane (CPP) magnetoresistance behavior with the applied field perpendicular to the plane (*R-H* loop). The product of resistance-area (*RA*) value of this device is in a similar range as the previously reported CPP SV structures with an in-plane

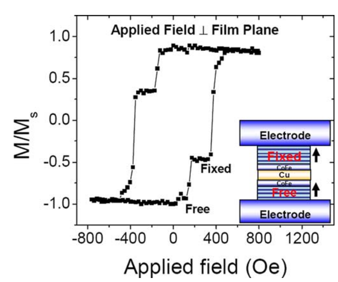

FIG. 1. (Color online) Hysteresis loop of the sheet film with the structure I. Applied field is perpendicular to the film plane. The switching fields of free and fixed layers were well separated. Inset: schematics of the spin valve structure with perpendicular anisotropy. The space layer (Cu) was sandwiched by two CoFe layers.[32]

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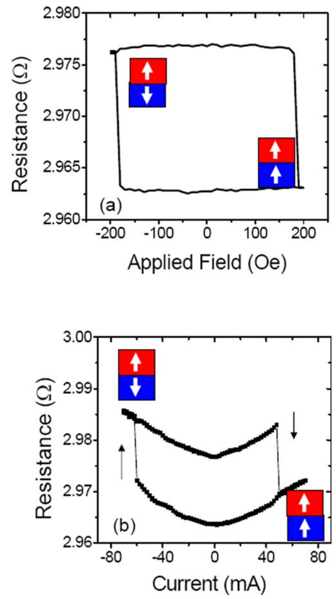

FIG. 2. (Color online) (a) Magnetoresistance loop of the structure I. Applied field is perpendicular to the film plane. (b) Resistance-current scanning loop of the structure I.

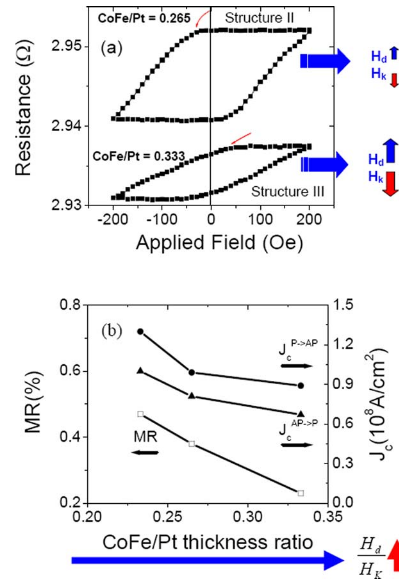

FIG. 3. (Color online) (a) Magnetoresistance loops of the structures II and III. Applied field is perpendicular to the film plane. (b) CoFe/Pt thickness ratio dependence of the CPP GMR and the critical switching current density.

anisotropy.[3–5,11–13,16–18] The CPP giant magnetoresistance (GMR) value obtained from Fig. 2(a) is 0.47%, which is a typical CPP GMR value.

The room temperature spin transfer behavior of the device (R-I loop) is displayed in Fig. 2(b). The positive current is defined along the direction from the bottom to top electrode. Current scanning starts from the antiparallel magnetization configuration (high resistance). The resistance slowly increases with the increase of the positive current, which is due to the increase of electron-magnon and electron-phonon scatterings.[3] When the current reaches a positive value (current density $J_1^{\mathrm{AP}-P}=1.0\times 10^8\ \mathrm{A/cm^2}$), the resistance sharply drops, which indicates the switching of the free layer magnetization to a parallel configuration with the fixed layer magnetization. The device resistance keeps low until the current sweeps back to a negative value (current density $J_1^{P-\mathrm{AP}}=-1.3\times 10^8\ \mathrm{A/cm^2}$), where the resistance returns to a high value in a single jump, which indicates that the free layer magnetization and fixed layer magnetization are antiparallel to each other again. Figure 2(b) shows that the device resistance has two clear switchings under a current scanning and the R-I loop is hysteretic. In comparison with Fig. 2(a), the two resistance values at zero current correspond to the high-low resistance values in the R-H loop for antiparallel and parallel configurations, respectively. The MR value (0.47%) obtained from R-I loop is the same as that obtained from R-H loop, indicating that the spin current fully switches the magnetization of the free layer. Since both the magnetization and sweeping currents are perpendicular to the film plane, this provides a strong support that the spin momentum transfer rather than the current-induced Oersted field drives the perpendicular magnetized free layer switching in the R-I scanning. However, either $J_1^{\mathrm{AP}-P}$ or $J_1^{P-\mathrm{AP}}$ is relatively larger than that in the previously reported Co/Cu/Co or CoFe/Cu/CoFe structures with in-plane anisotropy, respectively. This might be due to the spin depolarization by the Pt layers in both free and fixed layers.

The free layer moment rotation process is determined by the spin polarized current, demagnetization field (H_d), and perpendicular anisotropy field (H_k). It needs to be pointed out that the H_k here refers to the perpendicular interface anisotropy of $[\mathrm{CoFe/Pt}]_n$ multilayer rather than the final (or measured) anisotropy field of the multilayer system. This interface anisotropy field (H_k), controlled by the CoFe and Pt bilayer number and thickness ratio,[33,34] pulls the magnetic moment out of the plane while in general the demagnetization field (H_d) pushes down the magnetic moment in the plane. The final (or measured) anisotropy of this system is the competition result between H_d and H_k. As confirmed by Engel *et al.*,[32] the magnetic moment will be in plane (dominated by the demagnetization field) when the thickness of the sub-Co layer is larger than a critical value (smaller interface anisotropy).

It is noticed that H_d always tries to lie down the magnetic moment in the plane while H_k tries to pull it out of the plane. So that the 180° free layer rotation process can be divided into two sections: 0°–90° and 90°–180°. The 90° direction is in plane and 0° (180°) is out of plane. Free layer starts the rotation from 0° (180°). Before reaching the in-plane direction (90°), free layer is rotated by both H_d and the spin current. But H_k resists the rotation. After crossing the in-plane direction, both H_k and the spin current will pull up the free layer out of the plane. H_d, on the other hand, resists the rotation. Therefore, the competition between H_d and H_k will influence the free layer switching process. In order to further investigate the functions of H_d and H_k, two additional structures were designed: Si/SiO2/bottom electrode/Pt50/$[\mathrm{CoFe3.5/Pt17}]_5$/CoFeF5/Cu30/$[\mathrm{CoFe4/Pt23}]_7$/Pt30/top electrode (structure II) and Si/SiO2/bottom electrode/Pt50/$[\mathrm{CoFe4/Pt15}]_5$/CoFeF5/Cu30/$[\mathrm{CoFe4/Pt23}]_7$/Pt30/top electrode (structure III). In comparison with the free layer in structure I, CoFe/Pt thickness ratio in the free layer is increased from 0.233 to 0.265 and 0.333 for structures II and III, respectively.

Figure 3(a) shows the R-H loops of structures II and III with perpendicular applied field. For both of the structures, the shift of the nucleation field (red arrow) clearly shows that H_k is reduced since it comes from the interface effect and is in reverse of the CoFe thickness while H_d is increased at the same time. Figure 3(b) summarizes the MR values and critical current densities for all of the three structures as the function of CoFe/Pt thickness ratio. The MR ratios are 0.38% and 0.23% for structures II and III, respectively, which is lower than 0.47% for structure I. However, in comparison with structure I, $J_3^{\mathrm{AP}-P}$ and $J_3^{P-\mathrm{AP}}$ were reduced to 6.7×10^7 and 8.9×10^7 A/cm^2, respectively. As stated above, the net field is the competing result between H_d and H_k. H_d tries to lie down the magnetic moment in the plane in the spin transfer process for both current directions. But H_k tries to keep the moment direction out of the plane. Thus, the switching current density could be reduced by adjusting the CoFe/Pt thicknesses and ratios to achieve different H_d and H_k, as shown in Fig. 3(b).

In comparison with an in-plane spin transfer, in which both H_d and H_k block the free layer rotation, perpendicular spin transfer has the potential to achieve much lower critical current density as stated above. On the other hand, if we use the perpendicular magnetic field to pull up the moment, the moment switching ($P\rightarrow\mathrm{AP}$) under the sweeping current will be blocked by both H_d and H_{app} during the 90°–180° rotation. But the switching from $\mathrm{AP}\rightarrow P$ will be much easier because of the applied field. This will lead to a single switching curve in the *R-I* scanning and thus loss the hysteretic property. The detailed dynamic spin transfer behavior for the device with perpendicular anisotropy should be investigated in future.

A spin transfer behavior in nanomagnetic devices with a perpendicular anisotropy was reported. Although the intrinsic critical current density should be higher than the values shown above because the measurement was performed at room temperature, we believe the current work provide a solid base for the future spin-current-driven magnetic devices with perpendicular anisotropy.

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[1] J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[2] L. Berger, Phys. Rev. B **54**, 9353 (1996).
[3] J. A. Katine, F. J. Albert, E. B. Myers, D. C. Ralph, and R. A. Buhrman, Phys. Rev. Lett. **84**, 3149 (2000).
[4] F. J. Albert, J. A. Kattine, R. A. Buhrman, and D. C. Ralph, Appl. Phys. Lett. **77**, 3809 (2000).
[5] J. Grollier, V. Gros, A. Hamzic, J. M. George, H. Jaffes, A. Fert, G. Faini, J. Ben Youssef, and H. Le Gall, Appl. Phys. Lett. **78**, 3663 (2001).
[6] Y. W. Liu, Z. Z. Zhang, P. P. Freitas, and J. L. Martins, Appl. Phys. Lett. **82**, 2871 (2003).
[7] Y. Huai, F. Albert, P. Nguyen, M. Pakala, and T. Valet, Appl. Phys. Lett. **84**, 3118 (2004).
[8] G. D. Fuchs, N. C. Emley, I. N. Krivorotov, P. M. Braganca, E. M. Ryan, S. I. Kiselev, J. C. Sankey, D. C. Ralph, and R. A. Buhrman, Appl. Phys. Lett. **85**, 1205 (2004).
[9] J. Z. Sun, J. Magn. Magn. Mater. **202**, 157 (1999).
[10] R. H. Koch, J. A. Katine, and J. Z. Sun, Phys. Rev. Lett. **92**, 088302 (2004).
[11] Y. Jiang, S. Abe, T. Ochiai, T. Nozaki, A. Hirohata, N. Tezuka, and K. Inomata, Phys. Rev. Lett. **92**, 167204 (2004).
[12] Y. Jiang, T. Nozaki, S. Abe, T. Ochiai, A. Hirohata, N. Tezuka, and K. Inomata, Nat. Mater. **3**, 361 (2004).
[13] T. Y. Chen, Y. Ji, C. L. Chie, and M. D. Stiles, Phys. Rev. Lett. **93**, 026601 (2004).
[14] S. I. Kiselev, J. C. Sankey, I. N. Krivorotov, N. C. Emley, R. J. Schoelkopf, R. A. Buhrman, and D. C. Raloh, Nature (London) **425**, 380 (2003).
[15] B. Özyilmaz, A. D. Kent, J. Z. Sun, M. J. Rooks, and R. H. Koch, Phys. Rev. Lett. **93**, 176604 (2004).
[16] M. AlHajDarwish, H. Kurt, S. Urazhdin, A. Fert, R. Loloee, W. P. Pratt, and J. Bass, Phys. Rev. Lett. **93**, 157203 (2004).
[17] H. Kurt, R. Loloee, W. P. Pratt, and J. Bass, J. Appl. Phys. **97**, 10C706 (2005).
[18] X. Waintal and O. Parcollet, Phys. Rev. Lett. **94**, 247206 (2005).
[19] S. Zhang, P. M. Levy, and A. Fert, Phys. Rev. Lett. **88**, 236601 (2002).
[20] J. G. Zhu, J. Appl. Phys. **97**, 10N703 (2005).
[21] S. I. Kiselev, J. C. Sankey, I. N. Krivorotov, N. C. Emley, M. Rinkoski, C. Perez, R. A. Buhrman, and D. C. Ralph, Phys. Rev. Lett. **93**, 036601 (2004).
[22] I. N. Krivorotov, N. C. Emley, A. G. F. Garcia, J. C. Sankey, S. I. Kiselev, D. C. Ralph, and R. A. Buhrman, Phys. Rev. Lett. **93**, 166603 (2004).
[23] M. Covington, M. AlHajDarwish, Y. Ding, N. J. Gokemeijer, and M. A. Seigler, Phys. Rev. B **69**, 184406 (2004).
[24] N. Nishimura, T. Hirai, A. Koganei, T. Ikeda, K. Okano, Y. Sekiquchi, and Y. Osada, J. Appl. Phys. **91**, 5246 (2002).
[25] Y. F. Ding, J. H. Judy, and J. P. Wang, J. Appl. Phys. **97**, 10J117 (2005).
[26] Y. F. Ding, J. H. Judy, and J. P. Wang, IEEE Trans. Magn. **41**, 707 (2005).
[27] J. Shi, S. Tehrani, and M. R. Scheinfein, Appl. Phys. Lett. **76**, 2588 (2000).
[28] R. D. Gomez, T. V. Luu, A. O. Pak, K. J. Kirk, and J. N. Chapman, J. Appl. Phys. **85**, 6163 (1999).
[29] W. H. Rippard, M. R. Pufall, S. Kaka, S. E. Russek, and T. J. Silva, Phys. Rev. Lett. **92**, 027201 (2004).
[30] H. Meng, J. G. Wang, Z. T. Diao, and J. P. Wang, J. Appl. Phys. **97**, 10C926 (2005).
[31] Y. F. Ding, M. Pakala, P. Nguyen, H. Meng, Y. M. Huai, and J. P. Wang, J. Appl. Phys. **97**, 10C702 (2005).
[32] H. Meng and J. Wang, *50th Annual Conference on Magnetism and Magnetic Materials*, San Jose, CA, 30 October-3 November 2005, FA-10.
[33] B. N. Engel, C. D. England, R. A. V. Leeuwen, M. H. Wiedmann, and C. M. Falco, Phys. Rev. Lett. **67**, 1910 (1991).
[34] H. O. Daalderop, P. J. Kelly, and F. J. A. Den Broeder, Phys. Rev. Lett. **68**, 682 (1992).