Vortex Induced by DC Current in a Circular Magnetic Spin Valve Nanopillar

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We investigate the characteristic of vortex states induced by a dc current in trilayer circular magnetic nanopillars experimentally. Our samples are designed such that both the soft and hard layers can contain a magnetic vortex and the interlayer is thick enough such that only dipolar interaction is important. The relative chiralities between the two layers' vortex configurations as functions of external field and current are studied with various diameters. We also perform micromagnetic simulation on the magnetization reversals to compare with the magnetoresistance (MR) curves measured at low current and with current induced magnetization states. The current induced magnetization behaviors due to the spin transfer torque effect and the additional Oersted field are clearly identified on the resistance behavior.

***Index Terms*— Magnetic vortex state, spin transfer torque.**

I. INTRODUCTION

THE magnetic vortex state in spin valve ferromagnetic disk has become the focus of investigation [1]–[3] due to both fundamental interests and industrial applications. Several of the promising applications on vortex based devices including spintronics memories [4] and spin torque nano oscillators [5], [6] have been proposed. Thus, understanding the characteristics of the magnetic vortex under different external conditions is one of the main requirements for application of nanotechnology on related industry. The most interesting properties of nano disk shape magnetic materials are the formation of the two distinct states, a vortex state and a uniform state, during magnetization reversal. The vortex state is a closed curling magnetic structure around the outer part with a core at the center in the ferromagnetic disk pattern with the core magnetization pointing out of the plane. The vortex chirality can be either clockwise or counterclockwise and core polarity can be either direction out of plane. The vortex state has magnetic flux closure lines thus shows high stability and generates the smallest magneto static interaction between adjacent layers. Recently, the dynamics of vortex core magnetization excited by an electrical current has been introduced. The magnetic vortex core in nanoscale spin valve structure can be excited into persistent microwave frequency oscillations by a spin polarized dc current [5]. The oscillation of magnetic vortex is corresponding to the core being set into a steady circular motion around the center of the disk. Locatelli *et al.* [1] studied the dynamics of two coupled vortices driven by spin currents. Above a threshold current, a highly coherent microwave signal can be observed, with dependence on the relative polarities of the vortices. However, the detail of nucleation vortices configuration in response to spin transfer torque and current-induced Oersted field, which is a key for constructing a vortex based memory, has been lacking. Here, we investigate the characteristic of vortex states induced by a perpendicular dc current injection in trilayer circular magnetic nanopillars. The giant magnetoresistance (GMR) profile and the data of current induced magnetization switching have been measured. We have observed the behavior of nucleation of vortex state in disks with various diameters of samples. The micromagnetic simulations with the OOMMF code [7] were performed for analyzing the orientation of magnetizations.

II. EXPERIMENTAL METHODS

The samples of circular nanopillars having 90, 160, 380, and 450 nm diameters were fabricated by electron-beam lithography and ion beam etching. The size of nanopillar was checked from the Scanning Electron Microscope (SEM) image. Multilayers with structure $\mathrm{Cu(80\ nm)/Ni_{80}Fe_{20}(24\ nm)/Cu(6\ nm)/Ni_{80}Fe_{20}(6\ nm)/Au(150\ nm)}$ were first deposited onto oxidized silicon substrates at room temperature by magnetron sputtering as sketched in Fig. 1(a). The thickness of the sample was calibrated independently by an atomic force microscope (AFM). The estimated error on the thicknesses and lateral dimension was about 5 percent. The films were then patterned into desired shape. Top and bottom electrode leads were fabricated for four-probe resistance measurements. Fig. 1(b) shows an optical microscope image of one sample surrounded by $\mathrm{SiO_2}$ insulation and the four leads. Fig. 1(c) shows a Scanning Electron Microscope (SEM) image of a typical sample with 160 nm diameter before the top electrode was put on. The electrodes cover the whole diameter of the samples. To understand the interplay between the vortex chiralities and the influence by vertical current injection, we used magnetoresistance (MR) measurement results to compare with the micromagnetic simulation, in which a unit cell of $5 \times 5 \times 6\ \mathrm{nm}$ was used. The typical material parameters for Permalloy are saturation magnetization $\mathrm{M_S} = 8.0 \times 10^5\ \mathrm{A/m}$, exchange stiffness constant $\mathrm{A} = 1.3 \times 10^{-11}\ \mathrm{J/m}$, damping parameter $\alpha = 0.01$, and current polarization $\mathrm{P} = 0.4$. The current driven simulations was done by numerically solving

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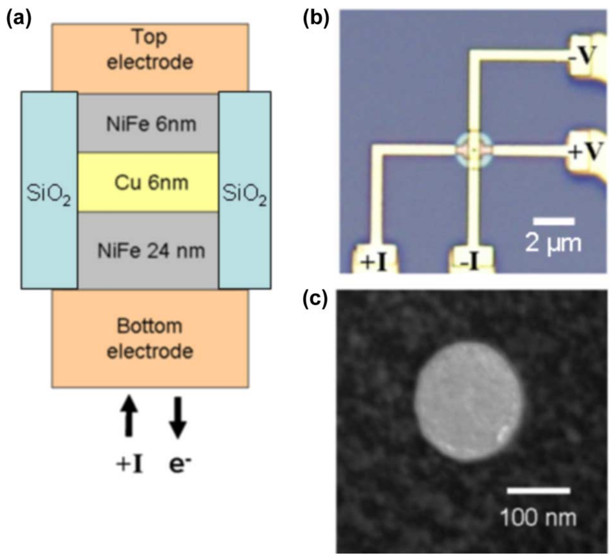

Fig. 1. (a) Sketch of the disk spin valve nanopillar stack. (b) Optical Microscope image of our device circuit. The light blue circular is SiO_2 and the sample is located at the center. (c) SEM image of a spin valve nanopillar sample with diameter 160 nm.

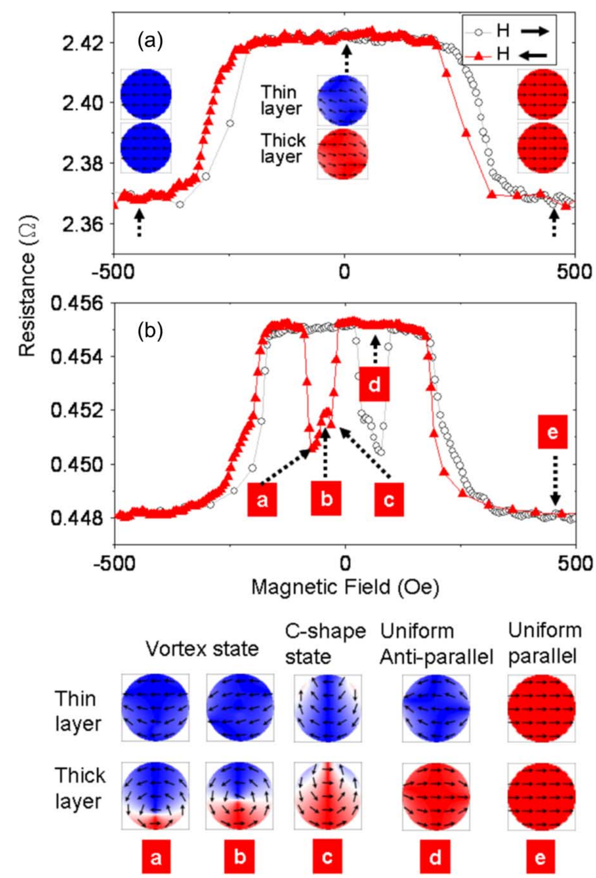

Fig. 2. Magnetoresistance curves of the samples with diameter (a) 160 nm (b) 380 nm. Micromagnetic simulations show the states of magnetization for the indicated external fields.

the Landau-Lifshitz-Gilbert equation with a spin momentum transfer term of Slonczewski's theory [10].

III. Results and Discussions

In Fig. 2, we present the MR signal when the external field was applied in plane to the film of the circular nanopillar with different diameters. The magnetization configurations of thin and thick NiFe layer in the reversal process have been investigation by micromagnetic simulation (see inset of Fig. 2). We observed that the variation of the MR profiles were markedly sensitive to the size of disk. For the circular nanopillar with 160 nm diameter, see Fig. 2(a), we observed the MR curve showing single transition between low resistance (saturation field), where the top and bottom magnetizations are parallel, to high resistance state (remanent field), where the magnetizations are antiparallel due to dipolar interaction. The MR curve is almost identical for both increasing and decreasing fields, suggesting a dominating dipolar interaction. Decreasing from saturation at 1000 Oe, the increase in the resistance occurs at 318 Oe, the plateau of maximum resistance is reached at magnetic field of 200 Oe with a MR ratio of 2.4%. At -240 Oe, the resistance shows sudden falling to saturation magnetization state. The data of 90 nm disk presented similar transition behavior with MR ratio of 1.5%. The remanent states of magnetic moments are favorable for the uniform, anti-parallel coupled single domains between the top and bottom magnetic layers with narrow diameter of disks. For the sample of 380 nm diameter, in which the MR ratio is 1.6% as seen in Fig. 2(b), we found double transition between the switching processes. The first high resistance state is reached at 175 Oe when decreasing the magnetic field from saturation. The magnetization of the two NiFe layers undergoes a direct change from uniform parallel to anti-parallel alignment due to dipole interaction. As the field is swept to negative values, the MR is switched at -60 Oe to an intermediate resistance state corresponding to nucleation of c-shape configuration in both magnetic layers with opposite chirality. The second transition of magnetic state occurs at -125 Oe and results in a high resistance value. The thick layer is in a vortex state at this region. Since the stray field from the thick layer vanishes after the nucleation of vortex state, the magnetization of the thin layer is no longer affected by the dipolar interaction from the thick layer. As a result, the orientation of magnetization in the thin layer becomes parallel to the external field to decrease the Zeeman energy. As the negative external field becomes stronger, the vortex core is moved from the center of the sample to the rim, then the resistance changes to a value corresponding to a uniform parallel alignment between the thin and thick layers. In this experiment, the vortex state is favorable for the large diameter (diameters 380 and 450 nm) and large thickness (NiFe 24 nm) layers of the samples in response to the magnetic field.

To study the characteristics of the samples in response to the spin transfer torque and the additional current-induced Oersted field, we performed the experiments of current perpendicular to structure plane induced switching processes by sweeping the dc current from 0 to $\pm$ 10 mA then back to 0 mA at zero external magnetic field. In our convention, a positive current corresponds to the electrons flowing from the thin layer to thick layer. The initial states were realized by external field sweeps from saturation to the remanent states. In Fig. 3, we show the variation of the resistance versus current curve measured with nanopillar of 160 nm diameter at zero fields, starting from the uniform anti-parallel configuration between the two magnetic layers (resistance of 2.42 Ω). Interestingly, we found irreversible variation of resistance dependence on the sign of the apply current. When the current is increased in the positive direction, we observe the resistance is reversed at $\mathrm{I} = +8.9\ \mathrm{mA}$ to a lower resistance state. This implies the injection of a perpendicular dc current produces an Oersted field that can lead to the nucleation of vortices configuration in both magnetic layers with parallel chirality. The transition from uniform anti-parallel to vortex state with parallel chiralities is associated with $\Delta\mathrm{R} = 0.04\ \Omega$ equal to about 65% of the full MR. This loss of MR is attributed to a loss of spin accumulation in the core region due to transverse spin diffusion [8]. When the current is swept back to zero value, the low resistance state is conserved until $\mathrm{I} = +3\ \mathrm{mA}$, then the resistance return to the initial state. By resetting the configuration of magnetization to uniform anti-parallel state with field sweep, followed by the injection of negative current, we observed two step reversals in the switching processes. The resistance is decreased at $\mathrm{I} = -3\ \mathrm{mA}$ to the first low resistance state corresponding to $\Delta\mathrm{R} = 0.022\ \Omega$. According to the previous experiments with the switching of nanopillars [9], we have confirmed the electrons from the thicker NiFe layer produces a spin polarized current that can apply a torque to the thinner NiFe layer towards the parallel alignment. Therefore, the first low resistance state at negative current are majorly controllable by the current through the spin transfer torque effect. In this situation, the magnetization of top layer reverses to the opposite direction, simultaneously the bottom layer switches from the uniform state to the vortex state. As the current increases to $\mathrm{I} = -9.5\ \mathrm{mA}$, we observe the second sharp decrease in resistance of $\Delta\mathrm{R} = 0.018\ \Omega$. The circumferential field tends to switch the thin NiFe layers into a vortex state, again the vortices configuration in both magnetic layers are with parallel chirality. When the current is swept back from -10 to 0 mA, the resistance jumps to the intermediate resistance state of 2.39 Ω ($\Delta\mathrm{R} = 0.025\ \Omega$) at $\mathrm{I} = -3.9\ \mathrm{mA}$. The configuration of magnetization is similar to the first step, the thick layer contained a vortex state and was stable even at zero current, the vortex in thin layer was annihilated at low negative current. It indicates the vortex state is less favorable for thin NiFe layer than the uniform state. We clearly demonstrate the processes to change resistance state in spin valve circular nanopillars by perpendicular dc current injection in both directions with significant dependence on the direction of current. The finial resistance state at zero current and field can be identified from the sign of injection dc current. This behavior of resistance switching can provide an advantageous approach to the development of spintronic devices.

In Table I we list the critical fields and currents for the vortex nucleation and annihilation in the soft layer and hard layer. From the magnetization switching by applied magnetic field, we observed the formation of vortex states in the hard layer with larger diameters. From the hysteresis loop of current driven measurements, the vortex state exists with all the sample geometries in both soft and hard layers. It can be seen that the range of vortex state, $\Delta I = I_a - I_n$, increased with increasing diameter in both layers. It indicated the stability of vortex state strongly depended on the diameter of the disk.

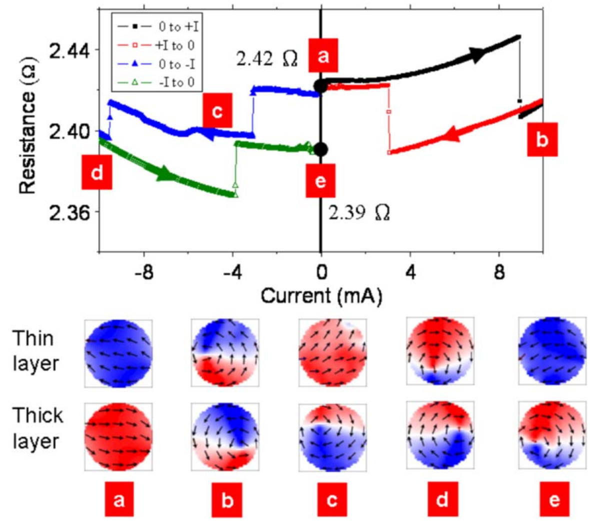

Fig. 3. Resistance versus current curves obtained with the uniform anti-parallel state at zero external field in the 160 nm diameter sample. Micromagnetic simulations show the configurations for the indicated perpendicular d. c. current.

TABLE I
MAGNETIZATION STATES OF THE LAYERS OF SAMPLES UNDER EXTERNAL MAGNETIC FIELDS AND APPLIED CURRENTS. WHEN THE VORTEX STATES EXIST, THE VORTEX NUCLEATION AND ANNIHILATION FIELDS (H_n, H_a) AND CURRENT (I_n, I_a) ARE LISTED

Sample diameter (nm)		90	160	380	450
soft layer	H_n (Oe)	Uniform state		C-shape state	
	H_a				
hard layer	H_n	Uniform state		31	5
	H_a			73	168
soft layer	I_n (mA)	-10.2	-9.5	-13.3	-18.5
	I_a	-6.5	-3.9	-2.4	5.0
hard layer	I_n	-2.8	-3.0	-3.6	-10.0
	I_a	-1.4	0.06	0.45	8.7

IV. SUMMARY

The characteristic of vortex states induced by a dc current in trilayer circular magnetic nanopillars was studied carefully. From magnetoresistance measurements, the relative chiralities of the top and bottom layer vortices can be revealed. When we compared our results with the micromagnetic simulation, the current induced magnetization behaviors due to the spin transfer torque effect and the additional Oersted field in samples with different diameters can be well understood. The vortex state is less favorable for thin NiFe layer than the uniform state. Therefore the current-induced switching is required to form vortex state in thin layers. We also found the finial resistance state at zero field depended on the original sign of injection dc current, which is a promising candidate for a memory cell for future nonvolatile data storage devices.

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