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Independent control of the vortex chirality and polarity in a pair of magnetic nanodots

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ABSTRACT

Independent control of the vortex chirality and polarity is realized by changing the in-plane magnetic field direction in nanodot pair through Object Oriented Micromagnetic Framework (OOMMF) simulation. The two magnetic circles are close to each other and have magnetic interaction. The two circles always have the same polarity and opposite chirality at every remanent state. There are totally four predictable magnetic states in the nanodot pair which can be obtained in the remanent state relaxed from the saturation state along all possible directions. An explanation on the formation of vortex states is given by vortex dynamics. The vortex states are stable in large out-of-plane magnetic field which is in a direction opposite to the vortex polarity. The geometry of the nanodot pair gives a way to easily realize a vortex state with specific polarity and chirality.

1. Introduction

It is well known that there is a vortex state in thin, soft ferromagnetic dot of submicrometer size [1–5]. The vortex state is the spin configuration with the lowest energy at zero applied magnetic field, which is the result of the competition among the magnetostatic energy, the quantum mechanical exchange energy, and the magnetic domain formation [6]. The vortex state can be characterized by two topological quantities: polarity, which is the up or down direction of the vortex core magnetization; chirality, which is the rotation direction of the in-plane magnetic moment, could be either clockwise (CW) or counterclockwise (CCW) [7]. The characterization implies that the vortex has four possible independent states; and can store the information of two magnetic bits. The nano-magnetic vortex has attracted extensive attention due to the magnetic memory has several advantages, *ie.* high storage density, fast feedback performance, and lower power consume to write and read the information [8].

Many works have been focused on the vortex state control in soft magnetic nanodots, such as the vortex core polarity using the field/current pulses [9–12] or the vortex chirality by introducing some geometry asymmetries in the nanodot [5,8,13–15]. However, few studies have focused on the simultaneous control of the chirality and the polarity of the vortex among them, particularly with a single parameter, which is the basis of the Vortex Magnetic Random Access Memory. Independent control of the polarity and the chirality of vortex can be achieved by an in-plane magnetic field with variable directions through magnetic asymmetry such as shape of the dot [8,16–19], or different thicknesses of two halves [20].

In this work, we presented a new way to realize the independent control of the vortex polarity and chirality by gathering two magnetic nanodots close to each other. The vortex chirality and polarity of the both dots will become adjustable due to the magnetostatic coupling interaction between them by changing the direction of in-plane magnetic saturation field. The magnetic state of the nanodot pair at multiple magnetic fields was investigated using the Object Oriented micromagnetic framework (OOMMF) [21]. Four stable ground states of vortices were obtained in the remanent state by only changing the direction of the in-plane applied saturating magnetic field. An explanation on the formation of vortex states is given by vortex dynamics. The stability of the vortex state is also analyzed in an out-of-plane field, various nanodot scale, and different sweeping speeds of the in-plane magnetic field.

2. Methods

The OOMMF was used to simulate the magnetic state of the permalloy nanodot pair in different magnetic fields. The standard parameters of permalloy were used in the simulation: saturation magnetization $Ms = 8 \times 10^5 (A/m)$, exchange constant $A = 1.3 \times 10^{-11}$ J/m, and a damping coefficient 0.01. The cell size was set as 3 nm to obtain sufficient accuracy according to the

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exchange length (lex = $\sqrt{2A/\mu_0 M_s} \approx 6$ nm) [22]. The two permalloy nanodots have identical diameter D = 180 nm and thickness T = 48 nm, the edge-to-edge gap between the two nanodots is D/20 = 9 nm. An in-plane magnetic field was previously applied to saturate and then decreased to zero along a certain direction with an angle θ relative to the X axis, in Fig. 1. Vortex states appear in the remanent states of the two nanodots. The vortex states of the two nanodots depend on the direction of the magnetic field and detail result was discussed as below.

3. Results and discussion

Firstly, the magnetic field is assumed along a fixed direction θ = 30° and varies from the maximum field 200 mT to 0 in 50 steps. The ramping speed is very low so that the nanodot pair reaches equilibrium state after field change in every step. The magnetization states of the nanodot pair at specific magnetic fields are shown in Fig. 2. The system is nearly in the saturated state at B = 200 mT, Fig. 2(a), which suggests most parts in the nanodot pair are magnetized along θ = 30° direction. It should be pointed that the parts in the middle of the two dots are magnetized to be approximately along θ = 0° direction due to the strong coupling between the two dots.

When the applied field decreases, the magnetization in the outer region of each dot gradually tends to be along the circle, while the region near the middle of the two dots still keeps the magnetization along x axis due to the strong coupling between the two dots. The magnetization distribution of the total system gradually transforms into an "S" shape from the uniform magnetization state as shown in Fig. 2(b). Approximate chiralities appear both in the two circles, CW in the left circle and CCW in the right one, which is coincide with the "S" shape. The magnetization keeps almost parallel everywhere in the top region of the left circle, while that changes dramatically in the bottom region, which will generate out-of-plane magnetization. As a result, when the magnetic field reduces to 28 mT, two vortex cores appear both at the bottom/top in the left/right circles respectively, in which the red color means that the polarization of the vortex cores were down.

When the applied field continues decreasing the two vortex cores would move toward center. The two vortices move to the center of each circle when the magnetic field is relaxed to zero as shown in Fig. 2(c), in which the two vortices have identical polarities but opposite chirality. The opposite chirality makes the nanodot pair at a minimum energy.

The vortex cores continue moving to opposite edges when the field is enhanced in the negative direction, and disappear at B = −132 mT, Fig. 2(d). The nanodot pair is in negative saturated state at B = −200 mT illustrated in Fig. 2(e). Then the magnetic field varies from −200 mT to 200 mT. The magnetization process of the nanodot pair is similar as that at the magnetic field varies from 200 mT to −200 mT, in Fig. 2(f) to Fig. 2(h). However, the remanent state relaxed from negative saturation, Fig. 2(g), is different from that relaxed from positive saturation shown in Fig. 2(c). They have the same down polarity but opposite chirality. The chirality are CW and CCW in left and right circles in Fig. 2(c), while in Fig. 2(g) it is CCW and CW in left and right circles, respectively.

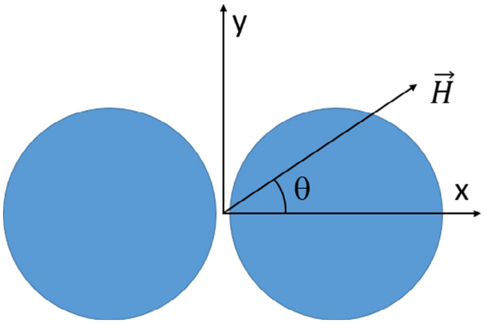

Fig. 1. Geometry of the nanodot pair. Each dot has the diameter D = 180 nm and thickness T = 48 nm. The gap between the two dots is D/20 = 9 nm. The magnetic field is along the direction with an angle θ relative to the X axis.

The in-plane and out-of-plane hysteresis loops of the nanodot pair are demonstrated in Fig. 3. The magnetization process and specific points are identical with those in Fig. 2. There is a typical double switch in the in-plane hysteresis which is similar as that in a single circle vortex [6]. The M_z at the relaxed state in the out-of-plane hysteresis loop is always negative both in the positive and negative magnetization process. The polarity in the nanodot pair is rather different with that in a single circle vortex since the polarity is unpredictable in a single circle vortex.

We will give an explanation by vortex dynamics on the formation of core polarity based on the work of Jaroslav Tóbik [23,24]. Let's take only the left circle for consideration. The formation of vortex core polarity is closely related to magnetization dynamic and can be described by the Landau-Lifshitz-Gilbert (LLG) equation

$$\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{M} \times \vec{H}_{eff} + \alpha \left(\vec{M} \times \frac{\partial \vec{M}}{\partial t} \right) \tag{1}$$

Let's consider the case when the applied field along the 30° direction is decreased from 200 mT to zero. The field change is so slow that the energy in the system is close to the local minimum at all times. Then $\frac{\partial \vec{M}}{\partial t} \approx 0$ everywhere. Therefore, at local minima $\mathbf{H}_{\text{eff}}$ is parallel to magnetization **M,** and can be written as $\mathbf{H}^{||}_{\text{eff}}$. Firstly, assume that the applied field **H** is above the nucleation field, and then decrease it by a small value △**H**. With the first approximation, the effective field can be written as $\mathbf{H}_{\text{eff}} = \mathbf{H}^{||}_{\text{eff}} + \triangle\mathbf{H}$. In a short time after the applied field is decreased the damping term can be neglected since α<<1. The *Z* component of magnetization can be given by the equation

$$\frac{\partial \vec{M}_z}{\partial t} = -\gamma(\vec{M}_x \times \Delta\vec{H}_y - \vec{M}_y \times \Delta\vec{H}_x) \tag{2}$$

With respect to the direction of applied field, the right hand side of Eq. (2) is not zero locally, nor it is on average because the magnetization distribution in each circle is asymmetric due to the coupling between the two circles (if θ ≠ 0°, 90°, 180°, 270°). The direction of the initial polarity evolution is obtained by the volume integration of Eq. (2). Therefore, it can be concluded that the magnetization is driven towards the well-defined direction by the asymmetry of magnetization distribution. The higher magnetization distribution asymmetry means more stable polarity.

In another case when the applied field along 210° is relaxed to zero from 200 mT, the $\vec{M}_x$, $\vec{M}_y$, $\Delta\vec{H}_x$ and $\Delta\vec{H}_y$ in Eq. (2) all have negative sign compared to those in the case when the field is along 30°. The $\frac{\partial \vec{M}_z}{\partial t}$ remains unchanged, which will make the polarity of the left circle identical in both direction of the applied field.

The polarity of the right circle can be deduced from the geometric symmetry. The left circle has the well-defined direction as discussed above for both directions 30° and 210°. The total system of the nanodot pair in the two cases when the field are along 30° and 210° are equivalent according to the geometric symmetry of the nanodot pair. It means the right circle when the field is along 30° is equivalent with the left circle when the field is along 210°. Then we can deduced that the polarities of two circles are always the same in both cases when the field is along 30° and 210°.

In above section it is shown that the nanodot pair has two different vortex states in a hysteresis loop when the applied magnetic