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Arrangement effects of nanocontacts on the magnetic vortex gyration in a confined multi-nanocontacts structure

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ABSTRACT

We studied the gyrotropic motion of a magnetic vortex in a multi-nanocontacts system, where spin-polarized out-of-plane dc currents were injected into a nanodisk through a centered nanocontact and several circle-distributed off-centered nanocontacts. It was found that the number of the off-centered nanocontacts, the direction combination of the currents, the current density, and the distance between the centered and the off-centered nanocontact all influence the gyrotropic motion of vortex, including vortex core orbits, eigenfrequency, and instantaneous gyrotropic frequency.

1. Introduction

Magnetic vortex is a curling magnetization distribution, with the magnetization pointing perpendicular to the plane within the nanometer size vortex core (VC). This magnetic state could be characterized by the polarity of the VC, pointing up ($p=1$) or down ($p=-1$), or by the curling direction of the in-plane magnetization, clockwise ($c=-1$) or counterclockwise ($c=1$) [1,2]. In 2007, Pribiag et al. firstly reported the spin-polarized dc-current-driven self-sustained oscillations based on magnetic vortex in a nanoscale spin valve structure [3]. The self-sustained oscillation of vortex refers to a displaced VC maintaining on a steady orbit with a characteristic value of eigenfrequency. Its associated microwave emissions occur at low current density, without external magnetic field, together with narrow width [4]. This spin-polarized current-induced vortex oscillators have created technology opportunities for spin torque nano-oscillators [5].

The nanopillar was firstly used to study the spin-polarized current-driven vortex oscillations [3,6,7]. However, due to the lateral confinement, when vortex is displaced from the center magnetic charges appear at the lateral surface increasing the dipolar stray field energy of the system and, therefore, the steady vortex oscillation can only occur within a very small current density range [8]. Then, the nanocontacts setup, where the current is injected into a multilayer element via a contact with the diameter about 10–100 nm, was found to be the most interesting devices [9–11]. This is because the steady vortex oscillation can occur in a very large current density range. Nevertheless, the effect of the dot size cannot be considered when we designing the associated device, meanwhile, a magnetic field or current with sufficient strength should be applied to the create a vortex in the continuous magnetic film. Taking these factors into consideration, we designed a confined nanocontact system, where the current is constrained into a nanocontact region in the nanopillar structure [12]. In such system, we found the steady oscillations of vortex can sustain in a wider current range, and the oscillation frequency becomes dependent on the VC position [12,13]. Moreover, if we introduce an off-centered nanocontact in the confined nanocontact system, the gyrotropic frequency shows zigzag variation with time or appears a peak in one circle, depending on the direction of the off-centered current [14]. So we think that the off-centered nanocontacts can be used to control the vortex oscillation in the confined nanocontact system. In consideration of the spin-torque devices with multi-nanocontacts have been experimently demonstrated [15–19], we design a confined multi-nanocontacts structure, where several off-centered nanocontacts are introduced into the confined nanocontact system. We calculate the vortex oscillations in such system to explore the arrangement effect of the off-centered nanocontacts.

2. Model and results

A circular-shaped Permalloy nanodot of $2R=400$ nm diameter and $L=10$ nm thickness was choosen to be the study object. Its ground state is a magnetic vortex with $(p, c)=(1, 1)$. To excite the

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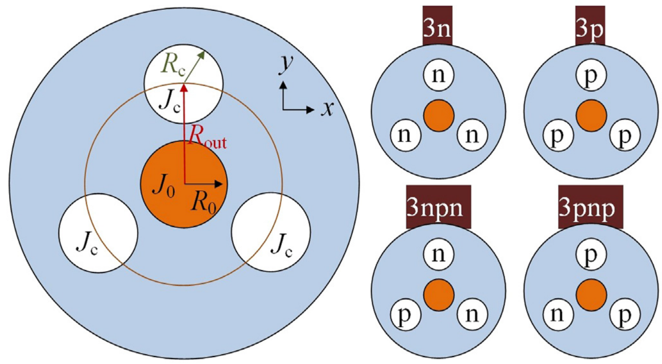

Fig. 1. Schematic illustration of a three off-centered nanocontacts system. One centered nanocontact with radius of R_0=50 nm (orange disk) and three off-centered nanocontacts with radius of R_c=30 nm (white disk) are arranged in a circular-shaped Permalloy nanodot of 2R diameter and L thickness, where the off-centered nanocontacts are evenly distributed in a circle of radius R_{out}. Out-of-plane spin-polarized currents are applied to the disk through these nanocontacts individually, where the current density of the centered (off-centered) current is J_0 (J_c). The letter p (n) denotes positive (negative) current, and the number "3" denote the number of the off-centered nanocontacts.

vortex, out-of-plane spin-polarized currents were applied to the nanodot through several nanocontacts. One of nanocontact (centered nanocontact) locates at the center of the disk with radius of R_0=50 nm, and the other nanocontacts (off-centered nanocontacts) with radius of R_c=30 nm are evenly distributed in a circle of radius R_{out} (As a example, Fig. 1 shows the sketch of a three off-centered nanocontacts structure). The number of the off-centered nanocontacts is defined as n_c, ranging from 3 to 6. As well, the direction of each current is different. Before description, we first define the current passes from $-z$ to $+z$ ($+z$ to $-z$) as positive (negative) current, which is denoted by p (n) in Fig. 1.The current applied to the centered nanocontact is always positive. Nevertheless, we allow both positive (p) and negative (n) current to inject into the off-centered nanocontacts. Although it was reported that magnetostatic interaction may influence the vortex motion [20], for simplicity we did not consider it, and we assume that the currents will pass through each of the contacts individually, where the current density of the centered current (off-centered currents) is J_0 (J_c). Then it can form four types of current combination (3n, 3p, 3npn, and 3pnp) for the three off-centered nanocontacts, as shown in Fig. 1, where the number "3" denote the number of the off-centered nanocontacts and the following letter combination represents the corresponding current combination. All these currents are characterized by spin polarization with the polarization direction along $-z$-axis.

The vortex gyration in such system was calculated by the Object Oriented Micromagnetic Framework (OOMMF) code, which is based on the Laudau–liftshitz–Gilbert equation extended by the Slonczewski spin-transfer torque [21]. In the micromagnetic simulation, the nanodisk was discretized into many small cells with each size of $2.5 \times 2.5 \times 10\ nm^3$, and the magnetic parameters used for Permalloy are as follows: the saturation magnetization $M_s = 8.6 \times 10^5\ A/m$, the exchange constant $A = 1.3 \times 10^{-11}\ J/m$, and the degree of spin polarization P=0.4. Also, we considered the Oersted field accompanying these current flows, which is computed with the Biot–Savart's law.

First, we study the vortex dynamical behaviors in this system after the currents applied. Fig. 2(a) shows the VC trajectories in a three off-centered nanocontacts system with R_{out}=120 nm. In all cases, the VC shows spirally motion until reach a steady-state orbit. This means that the steady oscillation of VC can be achieved in all current combinations. However, the shape of the steady-state orbits obviously is influenced by the current combination. For the

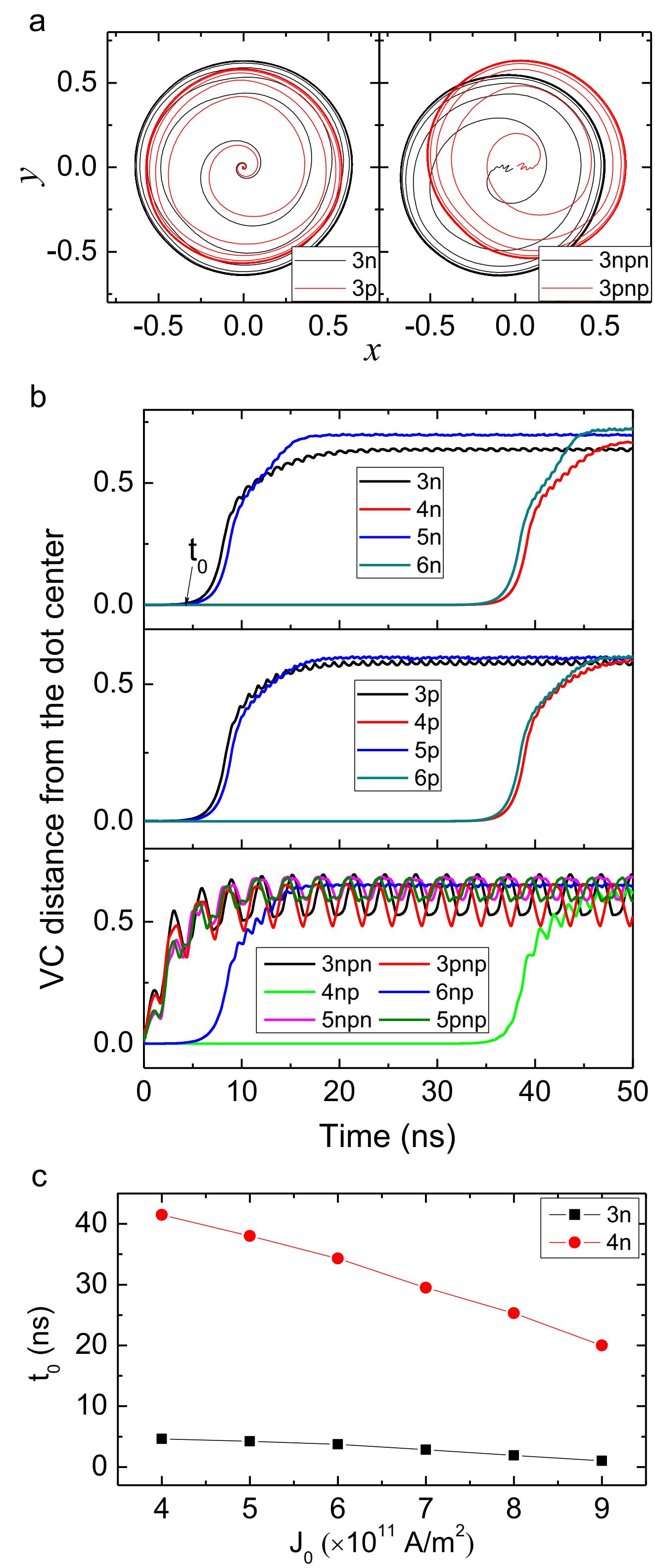

Fig. 2. (a) Spiral orbits of VC driven by spin polarized currents in a three off-centered nanocontacts system with R_{out}=120 nm for current combination 3n, 3p, 3npn, and 3pnp, where the current density $J_0 = 6 \times 10^{11}\ A/m^2$ and $J_c = 4 \times 10^{11}\ A/m^2$. (b) VC distance displaced from the disk center as a function of the simulation time. (c) Excitation time t_0 as a function of J_0 for current combination 3n and 4n, where R_{out}=120 nm and $J_c = 4 \times 10^{11}\ A/m^2$.