# Controllable Switching of the Fourfold Ground State of a Magnetic Vortex in Nanodots by Out-of-Plane Currents

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## 1. Introduction

Unique magnetic-vortex spin structures typically found in restricted magnetic thin-film dots of micron size or smaller [1] have attracted a great deal of interest. The vortex structure is characterized by an in-plane curling magnetization and an out-of-plane magnetization. Recently, ultrafast low-power consumption switching of either upward or downward vortex-core origination has been achieved by application of not only in-plane oscillating fields but also currents or their pulse form [2,3]. In this presentation we report on robust controllable switching of the vortex-core orientation (polarization, *p*) and the in-plane curling magnetization orientation (chirality,c), both of which are achieved by changing the density and direction of out-of-plane currents applied to the dots [4,5]. Then we propose a way to reliably control transitions between the individual fourfold states by applying different sequence combinations of individual single-step pulse currents [5].

## 2. Simulation Condition and Method

For the model, we used Permalloy (Py, $Ni_{80}Fe_{20}$) cylindrical dots of a radius $R$=100 nm and a different thickness. ($L$=10 and 17 nm) The initial ground state is either $(p,c)$=(+1,+1) or (+1,-1), where $p$ = +1(-1) corresponds to the upward (downward) core orientation pointing in the +z(-z) direction and $c$ = +1(-1) corresponds to the counter-clockwise (clockwise) curling in-plane orientation. We numerically calculated magnetization dynamic motions of individual unit cells (size: $2\times2\times L$ nm$^3$) in the Py dots using the OOMMF code that employs the LLG equation, including the so-called Slonczewski spin-transfer torque [6]. In order to conduct the model study of spin-polarized out-of-plane current-driven vortex excitations in the free-standing dots, we assumed that the spin polarization points in the -z direction. The current flow was in the +z direction. The circumferential Oersted fields (OHs) due to the current flow were taken into account using Biot-Savart's formulation.

## 3. Results

Fig. 1(a) shows distinct dynamic behaviors of the indicated vortex state of $(p,c)$=(+1,-1) in different regimes of the density $j_0$ of out-plane currents: no excitation in Regime $I_0$, low-frequency translation mode in Regime I, only p switching mode in Regime II, and both $p$ and $c$ switching in Regime III. Fig. 1(b) shows results for the other vortex states. Fig. 2 shows a promising means by which each of the fourfold ground vortex states can be simply but reliably manipulated by corresponding sequences of individual single-step pulse currents indicated by numbers in Fig. 2(b). Each step pulse has a characteristic threshold current density and direction. The details will be presented.

## 4. Conclusion

We found that the fourfold degenerate state (both polarization and chirality) of a magnetic vortex in soft magnetic dots can be manipulated simply by changing the density and direction of out-of-plane dc or pulse currents. It is proposed that individual switching from each vortex state to any of the other states is controllable with the different combination sequences of four characteristic single-step pulses.

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## 5. References

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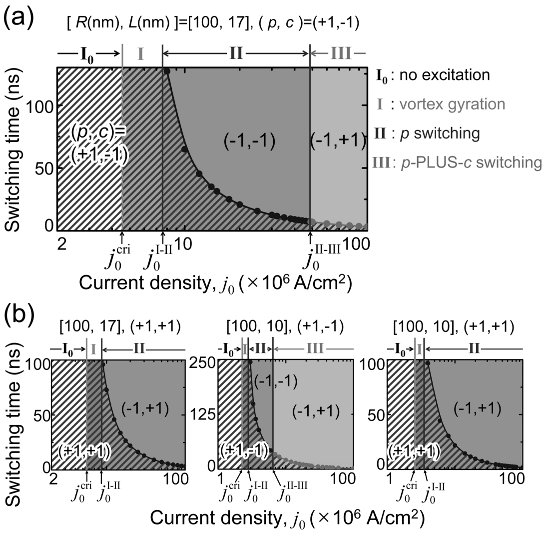

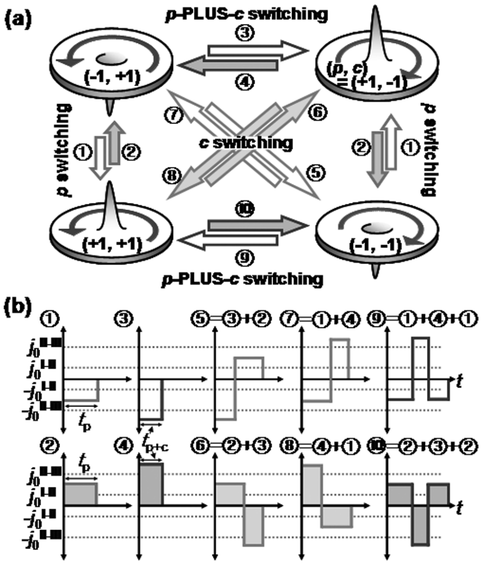

Fig. 1. Vortex-state switching diagrams versus current density, including no excitation, vortex gyration, p switching, and p-PLUS-c switching indicated by regimes, I0, I, II, and III for (p,c)=(+1,-1) in (a) and other states in (b) (Ref.[5]).

Fig. 2. Current pulse sequences (comprised of single, double or triple pulses) required for switching between the quadruple vortex states (Ref. [5]).