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Joint Effect of a Magnetic Field and a Spin-Polarized Current on Polarity Switching of Magnetic Vortices in a Spin-Transfer Nanooscillator

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The combined influence of a spin polarized current and an external magnetic field for switching the polarity of vortices in spin-transfer nanooscillators 400 nm in diameter is studied. A diagram is constructed of the dependence of the magnitude of the spin-polarized current on the magnitude of the magnetic field, which separately switches the polarity of the vortex in the magnetic layers of the spin-transfer nanooscillator.

Keywords: magnetic vortice, spin-transfer nanooscillator, magnetic nanodisk.

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A spin-transfer nanooscillator (STNO) is often a nanopillar that has two permalloy magnetic layers separated by a non-magnetic layer [1–4]. In magnetic layers a magnetic vortex can exist as the ground state [5]. There are two possible directions of magnetization in the center of the vortex (vortex polarity): up or down, which can be used, in particular, in digital memory devices. To use magnetic vortices, for example, in magnetic random access memory, it is necessary to be able to independently control the polarity and chirality of the vortex. For the case of a single magnetic vortex, two main polarity switching mechanisms were identified: „quasi-static" and „dynamic" [6,7]. The first can be realized with the help of an external magnetic field perpendicular to the plane of the disk, and the second with the help of a spin-polarized current.

The properties of a vortex STNO, when the magnetic vortex exists in each of the magnetic layers [8–14], largely depend on the polarity of the vortices. It is theoretically shown that with the help of a spin-polarized current it is possible to excite gyrotropic oscillations of magnetostatically coupled vortices with a constant frequency, which can change when the magnetic field is applied [12,13]. Previously, it was shown [12,15] that with the help of spin-polarized current, using the „dynamic" mechanism, it is possible to switch the vortex polarity only in a thick STNO magnetic layer. With the „dynamic" mechanism of polarity switching, when the initial vortex accelerates to a certain speed, a pair is generated from a new vortex with opposite polarity and an antivortex, followed by annihilation of the initial vortex with the antivortex. The mechanisms of polarity switching of magnetic vortices were studied using spin-polarized current and magnetic field for STNO of medium and small diameters [9,12,14]. In the present paper, we theoretically study the combined effect of the external perpendicular magnetic field and current on the separate switching of the vortices polarity in STNO of large diameter (400 nm), when the magnetic vortex cannot fly out of the edge of the disk.

Let us consider a nanopillar of circular cross section with a diameter of 400 nm. It contains three layers: a thick permalloy magnetic layer (15 nm thick), an intermediate non-magnetic layer (10 nm thick) and a thin permalloy magnetic layer (4 nm thick). The magnetic parameters of the system are as follows: saturation magnetization $M_s = 700$ and $600\,\mathrm{erg/(G\cdot cm^3)}$ for thick and thin layers, respectively, exchange rigidity $A = 1.2\cdot 10^{-6}$ and $1.12\cdot 10^{-6}$ erg/cm for thick and thin layers respectively, Hilbert damping parameter $\alpha = 0.01$, gyromagnetic ratio $\gamma = 2.0023\,(\mathrm{erg\cdot s})^{-1}$ [15]. The nonlinear dynamics of the magnetization vector $\mathbf{M}$ in the magnetic layer will be described using the generalized Landau–Lifshitz equation. It contains an additional torque [4] responsible for the current interaction with the magnetization, and has the form

$$\dot{\mathbf{M}} = -\gamma\left[\mathbf{M}\times\mathbf{H}_{eff}\right] + \frac{\alpha}{M_s}\left[\mathbf{M}\times\dot{\mathbf{M}}\right] + \mathbf{T}_{s.t.}. \qquad (1)$$

The effective field H_{eff} is the sum of the external magnetic field perpendicular to the nanodisk plane, the fields of magnetostatic and exchange interactions. The additional torque of equation (1) depends linearly on the current density and its polarization and consists of two components: parallel and perpendicular to the plane ($\mathbf{M}$, $\mathbf{m}_{ref}$), where $\mathbf{m}_{ref}$ — unit vector along the magnetization in another magnetic layer. For the numerical calculation of the coupled dynamics of magnetic vortices, the software package for micromagnetic modeling SpinPM [15,16] was used. We will study the dynamics of two coupled magnetic vortices with the same polarity (P-vortices) and chirality that exist at the initial time in each magnetic layer. Magnetic vortices

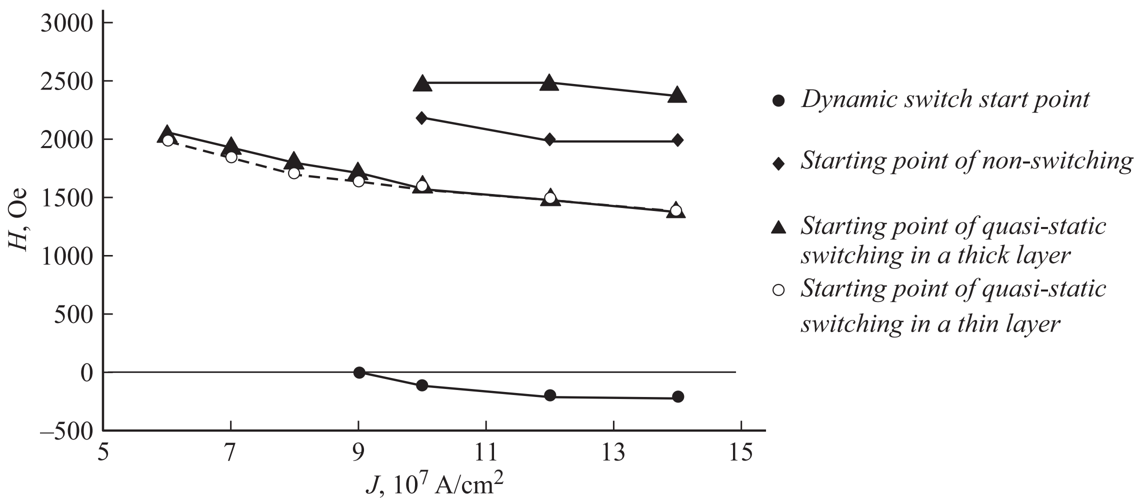

Figure 1. Dependence of the critical value of the magnetic field that switches the vortex polarity in thin and thick magnetic layers on the current density.

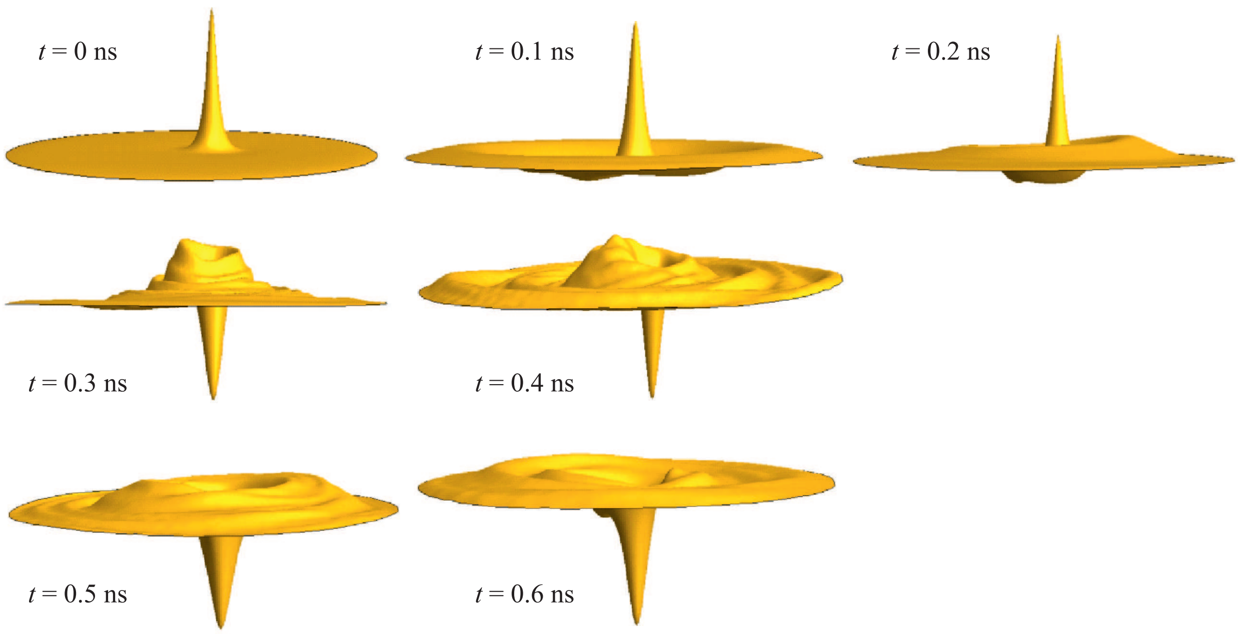

Figure 2. Three-dimensional distribution of the magnetization component along axis z, perpendicular to the plane of the disk, in a thick magnetic layer at different times.

with different polarity will be called AP vortices. Current polarization $P = 0.1$.

The numerical calculation was as follows. At a certain current density, we set different values of the external magnetic field and study the coupled vortex dynamics. From the analysis of the vortex dynamics the dependence on current of the critical value of the magnetic field, which switches the polarity of the vortex core, is found in thin and thick magnetic layers (Fig. 1). It can be seen from Fig. 1 that this dependence for the case of low currents is practically linear, the value of the critical field of polarity switching noticeably decreases (by more than 20%) with current increasing. The maximum value of the critical magnetic field for vortices in thin and thick layers at the minimum value of the considered current is 2000 and 2075 Oe. The value of the critical magnetic field at the same current is always smaller for vortex in the thin magnetic layer. The observed difference between the values of the critical fields for switching the polarity of vortices in thin and thick magnetic layers varies from 20 to 100 Oe, which can be used in practical applications. For the considered cases of low currents and P-vortices, switching of the vortex polarity in thin and thick layers was observed with a small vortex exit from the geometric center (Fig. 2). Such a mechanism of vortex polarity switching can be called „quasi-static“ [12,14]. The process of polarity switching is accompanied by the

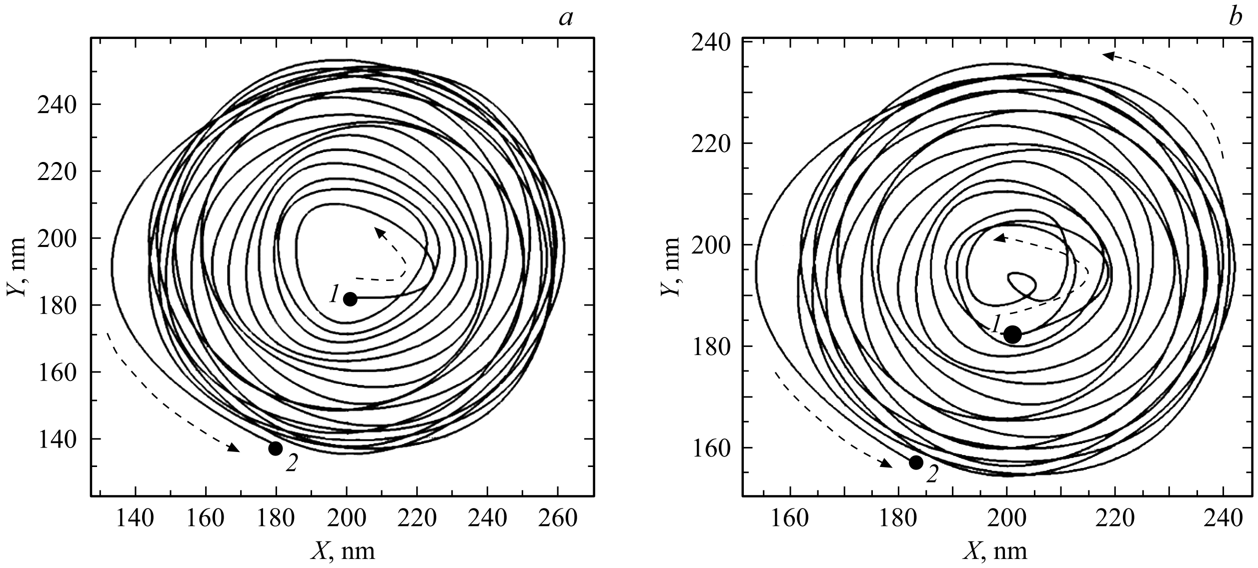

Figure 3. Trajectories of stationary motion of the vortex center in thick (a) and thin (b) magnetic layers at $j = 10 \cdot 10^7$ A/cm^2, $H = 2200$ Oe. Point *1*corresponds to time 0 ns, point *2* — 5.9 ns.

excitation of internal oscillation modes of the vortex and the emission of spin waves. The system needs about 1 ns after the field is turned on to go into a new unexcited stable vortex state. Note that the results obtained for nanopillar of large diameter (400 nm) differ noticeably from the results in the previously considered cases of average (200 nm) and small (120 nm) diameters [9,12,14]. For STNO with a diameter of 120 nm the critical magnetic switching field for vortex in thin layer at minimum current value is approximately 2500 Oe and practically does not depend on the current value, and for the vortex in thick layer it decreases linearly with current increasing from about 3200 Oe. For STNO with diameter of 200 nm, the critical magnetic field of polarity switching for vortex in thin and thick layers is practically independent of the current value and is approximately 2600 and 3400 Oe, respectively.

For the case of high currents, when the current value exceeds the critical value [15,16], sufficient to start the dynamic mechanism of the vortex polarity switching in thick layer, the dependence on the current of the magnetic field that switches the vortex polarity in a thin layer is similar to the case of low currents. And the process of vortex polarity switching in thick layer becomes much more complicated. For example, at a current density of $10 \cdot 10^7$ A/cm^2, four values of the critical magnetic field were already found. The value of the first critical field is approximately -100 Oe. For field values less than this value, no switching of the vortex polarity was found. At large values, a dynamic mechanism of polarity switching is observed. The value of the second critical field is approximately 1600 Oe. At field values less than this value, a dynamic scenario of the vortex polarity switching is realized, at large values a quasi-static switching mechanism is realized. The value of the third critical field is equal to 2200 Oe. At field values less than this value, a quasi-static mechanism of polarity switching is observed. For fields greater in va;lue, but lower the fourth critical field, no the vortex polarity switching is observed, but the stationary mode of coupled oscillations of the AP vortices reaches a steady state (Fig. 3). The fourth critical field corresponds to the field starting from which the quasi-static mechanism of the vortex polarity switching is again observed.

The presence of the first critical value of the field is explained by the fact that the field, which is negative in magnitude, complicates the dynamics of vortices and reduces the rotation frequency. With its sufficiently large absolute value, it does not allow the vortex to accelerate to the critical speed. The second value of the critical field, which leads to quasi-static mechanism of vortex polarity switching, is similar to the critical field value for the vortex in thin disk. The gap of the forbidden values of the magnetic field for the quasi-static switching mechanism, located between the third and fourth critical fields, was discovered for the first time, and its additional studies are needed to explain it.

Finally, note that for separate polarity switching of the vortices in STNO with large diameter (400 nm), a smaller magnetic field is required compared to the cases of medium and small diameter STNOs, which is more beneficial in terms of practical applications.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] K.A. Zvezdin, E.G. Ekomasov, Phys. Metals Metallogr., **123**, 201 (2022). DOI: 10.1134/S0031918X22030140.
[2] P.N. Skirdkov, A.F. Popkov, K.A. Zvezdin, Appl. Phys. Lett., **113**, 242403 (2018). DOI: 10.1063/1.5064440
[3] A. Litvinenko, V. Iurchuk, P. Sethi, S. Louis, V. Tyberkevych, J. Li, A. Jenkins, R. Ferreira, B. Dieny, A. Slavin, U. Ebels, Nano Lett., **20**, 6104 (2020). DOI: 10.1021/acs.nanolett.0c02195
[4] A.K. Zvezdin, K.A. Zvezdin, A.V. Khval'kovskii, Phys. Usp., **51**, 412 (2008). DOI: 10.1070/PU2008v051n04ABEH006508.
[5] K. Guslienko, Nanoscale Res. Lett., **9**, 386 (2014). DOI: 10.1186/1556-276X-9-386
[6] T. Okuno, K. Shigeto, T. Ono, K. Mibu, T. Shinjo, J. Magn. Magn. Mater., **240**, 1 (2002). DOI: 10.1016/S0304-8853(01)00708-9
[7] A.V. Khvalkovskiy, A.N. Slavin, J. Grollier, K.A. Zvezdin, K.Y. Guslienko, Appl. Phys. Lett., **96**, 022504 (2010). DOI: 10.1063/1.3291064
[8] S.S. Cherepov, B.C. Koop, V. Korenivski, D.C. Worledge, A.Yu. Galkin, R.S. Khymyn, B.A. Ivanov, Phys. Rev. Lett., **109**, 097204 (2012). DOI: 10.1103/PhysRevLett.109.097204
[9] N. Locatelli, A.E. Ekomasov, A.V. Khvalkovskiy, Sh.A. Azamatov, K.A. Zvezdin, J. Grollier, E.G. Ekomasov, V. Cros, Appl. Phys. Lett., **102**, 062401 (2013). DOI: 10.1063/1.4790841
[10] E. Holmgren, A. Bondarenko, B.A. Ivanov, V. Korenivski, Phys. Rev. B, **97**, 094406 (2018). DOI: 10.1103/PhysRevB.97.094406
[11] E. Holmgren, A. Bondarenko, M. Persson, B.A. Ivanov, V. Korenivski, Appl. Phys. Lett., **112**, 192405 (2018). DOI: 10.1063/1.5030855
[12] A.E. Ekomasov, S.V. Stepanov, K.A. Zvezdin, E.G. Ekomasov, Phys. Metals Metallogr., **118**, 328 (2017). DOI: 10.1134/S0031918X17020028.
[13] A. Hamadeh, N. Locatelli, V. Naletov, R. Lebrun, G. Loubens, J. Grollier, O. Klein, V. Cros, Phys. Rev. Lett., **112**, 257201 (2014). DOI: 10.1103/Phys. Rev. Lett.112.257201
[14] A. Ekomasov, S. Stepanov, E. Ekomasov, Pis'ma o materialakh, **6** (1), 46 (2016). (in Russian) DOI: 10.22226/2410-3535-2016-1-46-48
[15] E.G. Ekomasov, S.V. Stepanov, K.A. Zvezdin, N.G. Pugach, G.I. Antonov, Phys. Metals Metallogr., **122**, 197 (2021). DOI: 10.1134/S0031918X21030054.
[16] E.G. Ekomasov, S.V. Stepanov, V.N. Nazarov, K.A. Zvezdin, N.G. Pugach, G.I. Antonov, Tech. Phys. Lett., **47**, 843 (2021). DOI: 10.1134/S1063785021090030.