Modern Physics Letters B
Vol. 38, No. 21 (2024) 2440001 (9 pages)

DOI: 10.1142/S0217984924400013

Control of the memory cell magnetization by a combined pulse of local magnetic fields

Yu. I. Dzhezherya [*,†,**], P. Yu. Polynchuk [*,‖], I. V. Gerasimchuk [*,†], S. P. Kruchinin [‡,§], V. M. Kalita [*,†] and V. Korenivski [¶]

[*] *Institute of Magnetism, National Academy of Sciences of Ukraine and Ministry of Education and Science of Ukraine, Vernadsky Blvd. 36b, 03142 Kyiv, Ukraine*

[†] *National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Beresteisky Ave. 37, 03056 Kyiv, Ukraine*

[‡] *Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Metrolohichna str. 14b, 03143 Kyiv, Ukraine*

[§] *Felix Bloch Institute for Solid State Physics, Leipzig University, Linnéstraße 5, 04103 Leipzig, Germany*

[¶] *Nanostructure Physics, Royal Institute of Technology, 10691 Stockholm, Sweden*

[‖] *Donetsk Institute for Physics and Engineering named after O.O. Galkin, National Academy of Sciences of Ukraine, Nauky Ave. 46, 03028 Kyiv, Ukraine*

[**] *dui_kpi@ukr.net*

Received 25 December 2023
Accepted 7 January 2024
Published 17 February 2024

We study the process of controlling the states of a magnetic memory cell by a pulsed magnetic field. The magnetization dynamics of such a system is described by the Landau-Lifshitz equation. We find the optimal parameters of time dependence, amplitude and duration of magnetic field pulses created by currents in the control system, which provide a fast inertialess process of switching the magnetization of the functional element of the cell.

Keywords: Magnetic memory cell; non-volatile memory; magnetic random-access memory (MRAM); ultrafast magnetization reversal; device physics.

1. Introduction

The development and improvement of non-volatile magnetic memory with very high endurance and scalability remains an important issue in the field of nanomagnetism. Magnetic random-access memory (MRAM) is a key class of a magnetic memory of

[**] Corresponding author.

this type.[1–3] For such applications, it is critical to achieve reliable and ultrafast magnetization reversal[4] that surpasses conventional slow precessional switching which can take up to nanoseconds for the device magnetization vector reversal. It is shown in a number of works that in order to achieve the set goal, it is important to use pulses of magnetic field[5–15] and spin-polarized current[16–20] to initiate the process of switching the magnetic state of the functional element.

In particular, work[21] is devoted to a partial solution to the problem of reducing the duration of magnetization reversal, focusing on the numerical study of the magnetization dynamics of a monodomain ferromagnetic particle subjected to a single rectangular pulse of a magnetic field or a spin-polarized current of arbitrary orientation.

In this work, we theoretically investigate the problem of controlling the magnetization states of a magnetic memory cell using a *combined pulse of local external fields*. A local magnetic field can be created by pulses of electric currents of a certain shape, passed through regular conductors used to control memory cells. Its purpose is to break the collinearity of the magnetic moments of a spin polarizer with a fixed magnetic moment and a free magnetic layer, which is absolutely necessary for the initiation of magnetic moment transfer processes.

As a rule, the memory cell control system consists of two crossed current buses, between which the structural elements of the memory cell are located (see Fig. 1).

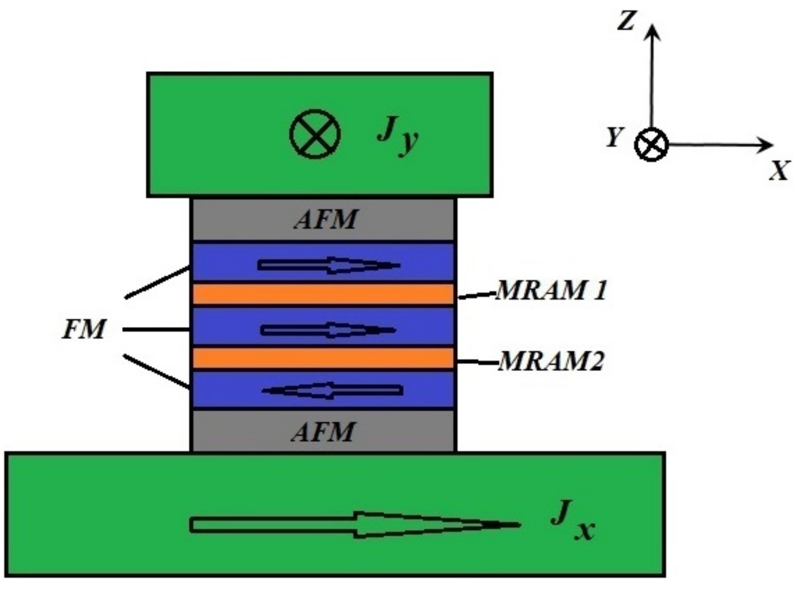

Fig. 1. (Color online) Scheme of a memory cell consisting of three ferromagnetic thin-film elements (FM) (arrows indicate directions of magnetization) located between two non-magnetic crossed buses (green) through which an electric current is passed. The thin-film FM elements have an elliptical shape with a small eccentricity and a long axis along the Ox direction. Thin MRAM 1 and MRAM 2 layers that differ from each other separate the FM elements. The upper and lower FM elements are pinned due to the presence of AFM interfaces.

The magnetization of such a system can be switched by passing a spin-polarized current through the functional element of the cell. However, the mode of pure field control remains out of consideration. This mode can be effectively organized in the system without any structural changes, if the time dependence and amplitude of the current pulses, that pass through the crossed current buses, are properly selected. An additional condition for the reliable operation of the device is that the direction of magnetization changes in the memory cell located at the intersection of the wires, and the magnetic state of the remaining cells located away from the intersection remains unchanged.

In this work, the optimal parameters of field (current) pulses will be determined to achieve a fast inertialess mode of switching the direction of the memory cell magnetization.

2. Equation of Magnetization Dynamics of the Functional Layer

The data storage element in the form of a memory cell is presented schematically in Fig. 1. This memory cell consists of three ferromagnetic thin-film elements (nanoparticles) (FM) located between two non-magnetic crossed buses (green) through which an electric current is passed. The upper and lower ferromagnetic elements are pinned due to the presence of an antiferromagnetic (AFM) interface. Thin MRAM layers that differ from each other separate the ferromagnetic elements.

We study the case when, under the action of specially selected configurations of electric current pulses and the creation of a magnetic field in the region of a selected cell, a rapid switching of magnetization occurs, which is not followed by long relaxation processes.

Let us write the Landau–Lifshitz equation for this system. In order to highlight the main idea of the work and to simplify the theoretical consideration, we will not take into account the dissipation in the system further on, because in the conditions of the process under consideration dissipation leads to minor changes in the final quantitative results. Thus, we have

$$\frac{d\boldsymbol{m}}{dt} = -\gamma[\boldsymbol{m} \times \boldsymbol{H}_{\mathrm{eff}}], \tag{1}$$

where $\boldsymbol{m}$ is the unit magnetization vector of the free layer, which plays the role of a functional element of the system, $\boldsymbol{H}_{\mathrm{eff}}$ is the effective magnetic field acting on the magnetic moment of the functional layer, $\gamma = 2\mu_B/\hbar$ is the gyromagnetic ratio, M_s is the saturation magnetization of the free layer, and $\boldsymbol{\mu}$ is the unit magnetization vector of the lower pinned layer.

As in Refs. 22 and 23, we will assume that the free magnetic layer has the shape of a flat ellipse with a small eccentricity. This determines the shape anisotropy of this system, which is formed under the influence of dipole–dipole interaction. On the one hand, the flat shape determines a large value of the demagnetization coefficient in the direction of the normal and, as a result, a planar arrangement of magnetization, and on the other hand, an equilibrium position of magnetization in the direction of the long half-axis of the ellipse is formed.

For this system to function as a memory cell, it is only necessary that the magnetic resistances of the upper and lower tunnel contacts are different.

According to studies[10,11] based on the fact that the flat shape of a magnetic particle contributes to the formation of significant easy-plane anisotropy, we will assume that $|m_z| \ll 1$. Therefore, with accuracy to the linear terms in m_z, the unit magnetization vector of the free layer can be written in the following form:

$$\boldsymbol{m} = \frac{\boldsymbol{M}}{M_s} = (\cos\varphi, \sin\varphi, m_z). \tag{2}$$

In turn, the unit magnetization vectors of the upper and lower pinned layers are equal to $\boldsymbol{\mu_1} = (1, 0, 0)$ and $\boldsymbol{\mu_2} = (-1, 0, 0)$, respectively. In the future, we consider that their magnetic moments are pinned due to the use of AFM interlayers. In the present scheme of the cell state control, the role of external magnetic interlayers is to create magnetoresistance effects, which determine the direction of magnetization of the free magnetic layer.

The effective field $\boldsymbol{H}^i_{\text{eff}}$, which takes into account magnetostatic contributions and the external magnetic field, has the form

$$\begin{aligned} H^x_{\text{eff}} &= -4\pi M_s N_x \cos\varphi + H_x, \\ H^y_{\text{eff}} &= -4\pi M_s N_y \sin\varphi + H_y, \\ H^z_{\text{eff}} &= -4\pi M_s N_z m_z. \end{aligned} \tag{3}$$

The magnetostatic fields created by the upper and lower magnetic layers compensate each other.

After substituting (2)–(3), we obtain the Landau–Lifshitz equation in new variables, which after certain simplifications take the following form:

$$\begin{aligned} \frac{d\varphi}{d\tau} &= -m_z, \\ \frac{dm_z}{d\tau} &= (N_y - N_x)\sin\varphi\cos\varphi - h_y\cos\varphi + h_x\sin\varphi, \end{aligned} \tag{4}$$

where $\tau = t \cdot \omega_0$, $\omega_0 = 8\pi M_s \mu_B/\hbar$, μ_B is the Bohr magneton, and $h_y = \frac{H_y}{4\pi M_s}$, $h_x = \frac{H_x}{4\pi M_s}$.

When deriving Eqs. (4), it was taken into account that $|m_z|$, N_y, N_x, $|h_y|$, $|h_x| \ll 1$ and $N_z = 1 - N_y - N_x \approx 1$. Thus, the terms no greater than the linear ones with respect to the small parameter were preserved in Eqs. (4).

The system of two equations (4) describing the behavior of the magnetization of the free layer is equivalent to one equation of the second order for the angular variable:

$$\ddot{\varphi} + (N_y - N_x)\sin\varphi\cos\varphi - h_y\cos\varphi + h_x\sin\varphi = 0. \tag{5}$$

Here and in the future, a dot above a physical quantity means the time derivative: $\dot{\varphi} = d\varphi/d\tau$.

Thus, Eq. (5) will be considered as a basis for building a theory of controlling the magnetic states of a memory cell.

3. Control of the Magnetization States by a Combined Pulse of the Magnetic Field

Let us assume that initially there are no magnetic fields, $\mathbf{h} = 0$, and the magnetization of the free layer is in a state of stable equilibrium, so that $\varphi = 0$, $\dot{\varphi} = 0$ at $\tau < \tau_1 = -\omega_0 T/2$. Further, at the moment of time τ_1, electric currents pass through the wires and create a magnetic field in the area where the cell is located. The action of the magnetic field lasts for time T and stops at the moment of time $\tau_2 = \omega_0 T/2$.

For fast inertialess switching of the direction of magnetization, it is necessary that at the moment of termination of the action of the pulsed magnetic field τ_2, the values of the angle and its time derivative approach the values $\varphi(\tau_2) \to \pi$, $\dot{\varphi}(\tau_2) \to 0$, respectively. It is under such a condition that the system will switch to a new stable state and will be at rest.

On the basis of the Maxwell's equation, rot $\boldsymbol{H} = 4\pi \boldsymbol{j}/c$, it can be easily demonstrated that the current flowing in a flat current bus in the direction Ox induces a magnetic field H_y, which at a distance much smaller than the width of the bus equals $H_y = \frac{2\pi}{c}\frac{I_x}{L}$ or $h_y = \frac{I_x}{2cM_sL}$, where c is the speed of light, L is the width of the bus, and I_x is the current flowing through the bus in the Ox direction. The values of physical quantities are determined in the SGS system.

It is clear that both components of the field, $h_y = \frac{I_x}{2cM_sL}$ and $h_x = \frac{I_y}{2cM_sL}$, will be present in the area between the intersection of two buses.

Let us assume that electrical equipment is capable of generating modulated currents of a special form (Fig. 2), the fields of which are described by the following time dependences:

$$\begin{aligned} h_x &= h_{x0}\mathrm{th}\nu\tau \cdot \theta\left(\tau + \frac{T\omega_0}{2}\right) \cdot \theta\left(\frac{T\omega_0}{2} - \tau\right), \\ h_y &= \frac{h_{y0}}{\mathrm{ch}\nu\tau}, \end{aligned} \tag{6}$$

where ν is the coefficient determining the degree of temporal localization of the magnetic field pulse, h_{y0} is the amplitude of the magnetic field along the Oy axis, and h_{x0} is the amplitude of the magnetic field along the Ox axis.

The initial conditions before turning on the magnetic field are $\varphi = 0$, $\dot{\varphi} = 0$ at $\tau < -T\omega_0/2$.

It turns out that only the action of the field in the Ox direction is not enough to start the magnetization reversal process from the state $\varphi_{\mathrm{I}} = 0$ to the state $\varphi_{\mathrm{II}} = \pi$, since the solution satisfying the formulated initial conditions is $\varphi = 0$. That is, even

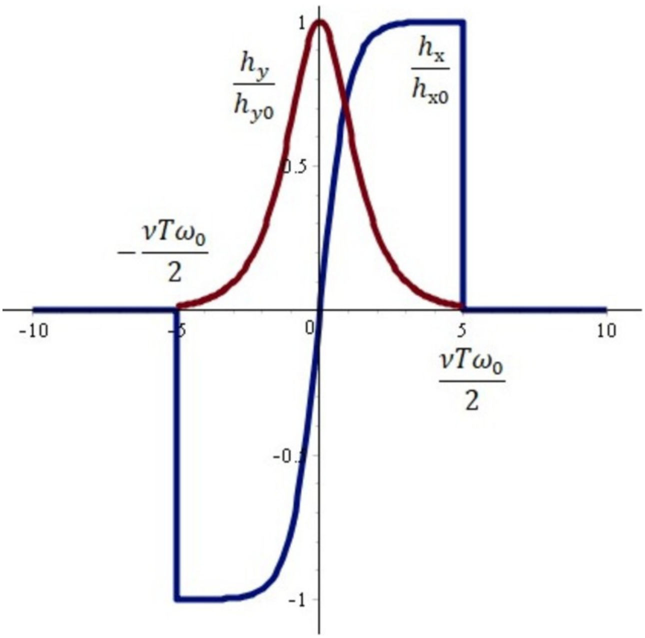

Fig. 2. (Color online) Impulse character of the external magnetic field.

in the presence of a large field in the Ox direction, the system will be in a position of unstable equilibrium, and its removal from this state is a random (non-deterministic) process. Therefore, to start the controlled magnetization reversal process, the action of the field pulse in the Oy direction is necessary, which makes the existence of a trivial solution of the type $\varphi \equiv 0$ impossible.

The only requirement imposed on the parameter ν is $\frac{\nu T\omega_0}{2} \gg 1$. That is, at the boundary of the time interval $[-\frac{T\omega_0}{2}; \frac{T\omega_0}{2}]$ the induced magnetic field has a negligibly small value. Therefore, we will look for the solution of Eq. (5), which describes the magnetization dynamics of the free layer, in the following form:

$$\varphi_{\rm II}(\tau) = 2\ \mathrm{arctg} e^{\nu\tau}, \tag{7}$$

and after substituting (7) into Eq. (5) we obtain

$$(-\nu^2 - (N_y - N_x) + h_{x0} + h_{y0})\frac{\mathrm{sh}\nu\tau}{\mathrm{ch}^2\nu\tau} = 0. \tag{8}$$

Equation (8) can have a real non-trivial solution only under the following conditions:

$$\nu_\pm = \pm\sqrt{h_{x0} + h_{y0} - (N_y - N_x)}. \tag{9}$$

It is obvious that the given initial conditions are satisfied by a positive value of the coefficient ν_+.

In order for expression (7) to be considered a solution of Eq. (5) with defined initial and final conditions, which describes the inertialess switching of the magnetization of the free layer, it must satisfy the following requirements with high accuracy:

$$\begin{aligned} &\varphi(\tau_1) = 0, \quad \dot{\varphi}(\tau_1) = 0, \\ &\varphi(\tau_2) = \pi, \quad \dot{\varphi}(\tau_2) = 0. \end{aligned} \tag{10}$$

Substituting the function (7) into the expressions for the boundary conditions (10) and taking into account the discussed requirements ($\nu T\omega_0/2 \gg 1$), we obtain

$$\begin{aligned} &\varphi(\tau_1) = 2\ \mathrm{arctg} e^{-\frac{\nu T\omega_0}{2}} \to 0, \\ &\varphi(\tau_2) = 2\ \mathrm{arctg} e^{\frac{\nu T\omega_0}{2}} \to \pi, \\ &\dot{\varphi}(\tau_1) = \dot{\varphi}(\tau_2) = \frac{\nu}{\mathrm{ch}(\nu T\omega_0/2)} \to 0. \end{aligned} \tag{11}$$

Thus, function (7) under the specified conditions describes with great accuracy the process of fast and almost inertialess switching of the magnetization of the free functional layer from the state $\varphi_{\mathrm{I}} = 0$ to the state $\varphi_{\mathrm{II}} = \pi$. In this mode, the residual perturbations of magnetization in the cell under consideration will have a negligibly small value, which indicates that the technical conditions are met.

Note that if the form of the field signals has slight deviations from those given in (6), then this will lead to only small perturbations in the system, which will be accompanied by small oscillations of the magnetization around the new equilibrium position.

In order for the process of guaranteed magnetization reversal to take place in the functional free layer, which is located between the intersection of two current buses and does not affect the rest of the memory cells, the following conditions must be met:

$$h_{x0}; \quad h_{y0} < (N_y - N_x) < h_{x0} + h_{y0}. \tag{12}$$

It should be noted that in the functional elements located above the bus with current, parallel recording processes can also be carried out, which can speed up the recording speed.

Therefore, with a proper choice of the configuration of the field perturbation $h_y(\tau)$, $h_x(\tau)$ and the pulse duration T, it is possible to achieve a regime of fast and almost inertialess switching of the magnetization of the free layer from the state $\varphi_{\mathrm{I}} = 0$ to the state $\varphi_{\mathrm{II}} \approx \pi$.

4. Conclusion

In this work, we theoretically investigated the problem of controlling the magnetization states of a magnetic memory cell using a combined pulse of local external fields. A local magnetic field can be created by pulses of electric currents of a certain shape, passed through standard conductors to control memory cells. It is shown that with a proper selection of the configuration of the field perturbation (correct selection of the configurations of electric currents in the conductive buses) and the duration of the pulse, it is possible to achieve a regime of fast and almost inertialess switching of the magnetization of the free layer (functional element) with a transition from one equilibrium state to another. We proposed the methods of controlling the magnetization states of the memory cell in the high-speed inertialess mode of switching the direction of the memory cell magnetization at the lowest values of the current density. The optimal forms, sequences and amplitudes of field pulses have been determined.

Acknowledgments

This work was partially supported by the Ministry of Education and Science of Ukraine (Project No. 0122U002233), the National Academy of Sciences of Ukraine (Project No. 0121U108844), and the European Project H2020-MSCA-RISE-2017-778308–SPINMULTIFILM.

ORCID

Yu. I. Dzhezherya https://orcid.org/0000-0003-1560-9567
P. Yu. Polynchuk https://orcid.org/0000-0001-8786-0465
I. V. Gerasimchuk https://orcid.org/0000-0002-2208-7050
S. P. Kruchinin https://orcid.org/0000-0002-0674-5826
V. M. Kalita https://orcid.org/0000-0001-6329-9095
V. Korenivski https://orcid.org/0000-0003-2339-1692

References

1. J. M. Slaughter, R. W. Dave, M. DeHerrera, M. Durlam, B. N. Engel, J. Janesky, N. D. Rizzo and S. Tehrani, *J. Supercond.* **15** (2002) 19.
2. S. Parkin, X. Jiang, C. Kaiser, A. Panchula, K. Roche and M. Samant, *Proc. IEEE* **91** (2003) 661.
3. D. Apalkov, B. Dieny and J. M. Slaughter, *Proc. IEEE* **104** (2016) 1796.
4. Q. F. Xiao, B. C. Choi, J. Rudge, Y. K. Hong and G. Donohoe, *J. Appl. Phys.* **101** (2007) 024306.
5. T. Devolder, J. Hayakawa, K. Ito, H. Takahashi, S. Ikeda, P. Crozat, N. Zerounian, J.-V. Kim, C. Chappert and H. Ohno, *Phys. Rev. Lett.* **100** (2008) 057206.
6. C. Thirion, W. Wernsdorfer and D. Mailly, *Nat. Mater.* **2** (2003) 524.
7. H. W. Schumacher, C. Chappert, P. Crozat, R. C. Sousa, P. P. Freitas, J. Miltat, J. Fassbender and B. Hillerbrands, *Phys. Rev. Lett.* **90** (2003) 017201.
8. Yu. I. Gorobets, Yu. I. Dzhezherya and A. F. Kravets, *Metallofiz. Noveishie Tekhnol.* **25** (2003) 27.
9. A. Konovalenko, E. Lindgren, S. S. Cherepov, V. Korenivski and D. C. Worledge, *Phys. Rev. B* **80** (2009) 144425.
10. Yu. I. Dzhezherya, K. O. Demishev and V. N. Korenivskii, *J. Exp. Theor. Phys.* **115** (2012) 284.

11. Yu. I. Dzhezherya, V. P. Yurchuk, K. O. Demishev and V. N. Korenivskii, *J. Exp. Theor. Phys.* **117** (2013) 1059.
12. S. S. Cherepov, V. Korenivski and D. C. Worledge, *IEEE Trans. Magn.* **46** (2010) 2112.
13. S. S. Cherepov, B. C. Koop, Yu. I. Dzhezherya, D. C. Worledge and V. Korenivski, *Phys. Rev. Lett.* **107** (2011) 077202.
14. B. C. Koop, Y. I. Dzhezherya, K. Demishev, V. Yurchuk, D. C. Worledge and V. Korenivski, *Appl. Phys. Lett.* **103** (2013) 142408.
15. B. C. Koop, T. Descamps, E. Holmgren and V. Korenivski, *IEEE Trans. Magn.* **53** (2017) 4300505.
16. S. Zhang, P. M. Levy and A. Fert, *Phys. Rev. Lett.* **88** (2002) 236601.
17. Y. Huai, M. Pakala, Z. Diao and Y. Ding, *Appl. Phys. Lett.* **87** (2005) 222510.
18. T. Devolder, C. Chappert, J. A. Katine, M. J. Carey and K. Ito, *Phys. Rev. B* **75** (2007) 064402.
19. K. Rivkin and J. B. Ketterson, *Appl. Phys. Lett.* **88** (2006) 192515.
20. D. C. Worledge, *IEEE Magn. Lett.* **8** (2017) 4306505.
21. P. P. Horley, V. R. Vieira, P. M. Gorley, V. K. Dugaev, J. Berakdar and J. Barnaś, *J. Magn. Magn. Mater.* **322** (2010) 1373.
22. C. Maufront, J.-V. Kim, T. Devolder, R. Fournel and C. Chappert, *IEEE Trans. Magn.* **41** (2005) 2655.
23. A. F. Kravets, D. M. Polishchuk, V. A. Pashchenko, A. I. Tovstolytkin and V. Korenivski, *Appl. Phys. Lett.* **111** (2017) 262401.