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Exchange spring-like inhomogeneous states in a ferromagnetic wire with current

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Transverse structure of magnetization in a ferromagnetic film induced by magnetic field of electric current has been analyzed. Two steps of arising exchange spring evolution are shown. The first one (weak current) is gradual twisting of magnetization aside from the wire axis. Above some critical current the transient area is compressed and localized near the middle plane. In presence of additional conductive layer the transient structure becomes asymmetric resulting to non-zero lateral component of the net magnetization. It is shown also that the mentioned asymmetry can provide additional displacement of domain walls after the electric current pulses.

Keywords: spintronics, domain wall dynamics, exchange spring, ferromagnet.

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For several decades now, the interaction of an electric current with a ferromagnetic domain structure has been one of the central issues of spintronics [1–10]. A significant number of mechanisms have been proposed for the effect of current carriers on inhomogeneous magnetization, including adiabatic and nonadiabatic transfer of spin momentum, as well as spin-orbit interaction through the Rashba effect, the Dzyaloshinskii–Moriya interaction, etc. [11–17]. Each new mechanism is described by introducing an additional term into the Landau–Lifshitz equation, while numerical simulation and data fitting allow one to judge the importance of the considered interaction in a particular experiment. Despite a huge number of studies, the question of the prevalence of one or another mechanism in each specific case remains open, and the interpretation of the data obtained is constantly changing.

An alternative to this approach, which treats the interaction of a ferromagnet with a current as the sum of individual effects of electrons, is the consideration of stationary magnetic fields in the framework of Maxwell's classical magnetostatics. Analysis of the restructuring of magnetization under the action of a global field surrounding an electric current made it possible to successfully explain the experimentally observed slope and transformation of domain walls [18–21]. Nevertheless, today it is generally accepted that the field mechanism of current interaction with domain walls is less important than spin-orbit effects due to the various orientation of the current field along the sample and the smoothening effect of the exchange energy at a small film thickness [22,23].

The last consideration deserves special attention. The global current field causes an inhomogeneous deviation of the magnetization from the equilibrium direction. The theory of this phenomenon, known in English literature as fanning or scissoring [24,25], is described, for example, in the work [24]. The calculated deviation of the magnetization angle (considered as a small parameter) for the numerical values used turned out to be on the order of several tens of degrees. Since the publication of this work, both the film sizes and the characteristic values of the current density have changed significantly; therefore, in order to compare the effectiveness of various mechanisms of current interaction with the domain structure in modern experiments, this estimate needs to be updated. In this case, the region of strong currents, corresponding to a magnetization deviation of 90°, as well as intermediate regimes, seems to be the most interesting.

In this article, the evolution of the current-induced transient magnetization structure is traced in a wide range of current values. To estimate the energy, a simplified linear model is used, so that the structure and equilibrium parameters of the exchange spring differ somewhat from the exact results expressed in terms of elliptic integrals [26]. Nevertheless, this approach, which has great clarity and simplicity of calculations, well describes the basic principles that determine the evolution of the transition structure with a change in the current density and other parameters, and the deviation of the domain wall width and the exact magnetization profile in the region of „the tails" does not exceed several percent [27,28].

Consider a long thin flat ferromagnetic wire $2t$ thick and $2w$ wide. The length of the wire is assumed to be infinite, and its width is much greater than its thickness. Due to the shape anisotropy, in the absence of external fields and current, a homogeneous state of magnetization along the long axis of the wire z will correspond to the lowest energy: $m_z = 1$, $m_x = m_y = 0$. Here, $m_i = M_i/M$ describes the magnetization components along three coordinate axes, the x axis is directed perpendicular to the film plane, the y axis along its width.

Uniform electric current with density j (total current $I = 4jtw$) creates a transverse magnetic field inside the wire. Its components H_x and H_y at any point can be calculated using the formulas given in [29]. In practice, the H_x field turns out to be less important, since the magnetization deviation perpendicular to the film plane is effectively suppressed by stray fields (the demagnetization factor in this direction is close to one). Considering only the field in the H_y plane far from the side edges of the stripe, we can confine ourselves to the simplified formula

$$H_y(x) = (2\pi/5)jx, \tag{1}$$

where the current density is expressed in Amperes per square centimeter, the thickness is in centimeters, and the field is in Oersteds [24,29]. The field is equal to zero in the middle plane of the sample, varies linearly with the coordinate, and reaches a maximum (in absolute value) on the film surface. Under the action of this field, the magnetization will deviate from the z axis, and the magnitude of the deviation is determined by the balance of magnetic and exchange energies. The largest deviation can be expected on the film surface, where the field is maximum; in the middle plane, where the field is zero, the magnetization is still directed along the z axis. Such a spatial turn of the magnetization under the action of magnetic and exchange forces is similar to the phenomenon of „an exchange spring", well known in the physics of magnetic layered structures [30,31]. The role of the hard layer, which fixes the direction of magnetization in one of the planes, is played in this case by the middle plane, where the field is equal to zero.

We will approximate the distribution of magnetization over the film thickness by a linear function

$$m_y(x) = (v/u)x, \tag{2}$$

where u and v are two fitting parameters characterizing the half-width and amplitude of the magnetization profile. Formula (2) is applicable in the middle region $|x| \leq u$, for the rest of the film $m_y = \pm v$. Both parameters are determined from the minimization of the total energy, consisting of the exchange and magnetic parts

$$W = \int\limits_{-t}^{t} \big(A(\partial m_y/\partial x)^2 - M m_y(x) H_y(x)\big) dx. \tag{3}$$

Here A is the exchange stiffness constant. Integrating this expression using equations (1) and (2), we obtain

$$W = 2Av^2/u - (2\pi/5)jMv(t^2 - u^2/3). \tag{4}$$

Minimization with respect to two parameters gives their equilibrium values

$$u = t\sqrt{3/5}, \tag{5}$$

$$v = 2\pi Mj(25A)^{-1}t^3\sqrt{3/5}. \tag{6}$$

The parameter u within the framework of the used model turns out to be constant and does not depend on the current, while the parameter v increases linearly with it. This corresponds to a gradual twisting of the exchange spring at a constant width, and the transition region occupies a very significant part of the sample. The value v, obviously, cannot be greater than one, therefore expressions (5) and (6) are valid at a current density below the critical one, determined by the condition $v = 1$:

$$j_c = 25\sqrt{5/3}A(2\pi Mt^3)^{-1}. \tag{7}$$

At higher currents $v \equiv 1$, and only one free parameter u remains. Minimizing the expression (4) with respect to it, we obtain for the region $j > j_c$

$$u = \left(\frac{15A}{2\pi jM}\right)^{1/3}. \tag{8}$$

We see that the second stage in the evolution of the exchange spring with increasing current consists in its gradual compression and localization in the middle part of the film. The change in the calculated magnetization profiles with increasing current along with the dependences (5), (6), (8) are shown in Fig. 1.

The dependence of the total energy of the system on the current in both regions (above and below j_c) is found by substituting the equilibrium parameters u and v into equation (4). As expected, at the point j_c the curve has a singularity (break point):

$$W(j) = -2(5/3)^{1/2}At^{-1}(j/j_c)^2, \tag{9}$$

for $j < j_c$,

$$W(j) = \big(2At^{-1}(5/3)^{1/2} + (6\pi/25)Mt^2\big)(j/j_c)^{1/3} - (2/5)\pi Mt^2 j \tag{10}$$

for $j > j_c$. At currents below the critical value, the energy gain is quadratic in current, and then it becomes close to linear, and in both cases the energy is negative due to the interaction of the magnetization with the field.

Let us now consider a similar problem in the presence of a second current-carrying (nonmagnetic) layer in the immediate vicinity of the main film. This situation is typical for modern experiments, which are usually carried out on structures consisting of a fairly large number of layers. As a rule, in numerical estimates only the strongest field created by one of the layers is taken into account; the contributions of weaker currents are most often omitted. We will see, however, that a number of effects are related not to the magnitude of the additional field, but to the asymmetry of the problem introduced by it.

The magnetic field H_1, created outside the additional layer by the current flowing through it, decreases with distance, reaching the dependence $1/x$ at infinity [29]. A noticeable drop in the field occurs at distances of the order of the wire width, therefore, within the boundaries of the main ferromagnetic layer H_1 can be considered a constant value.

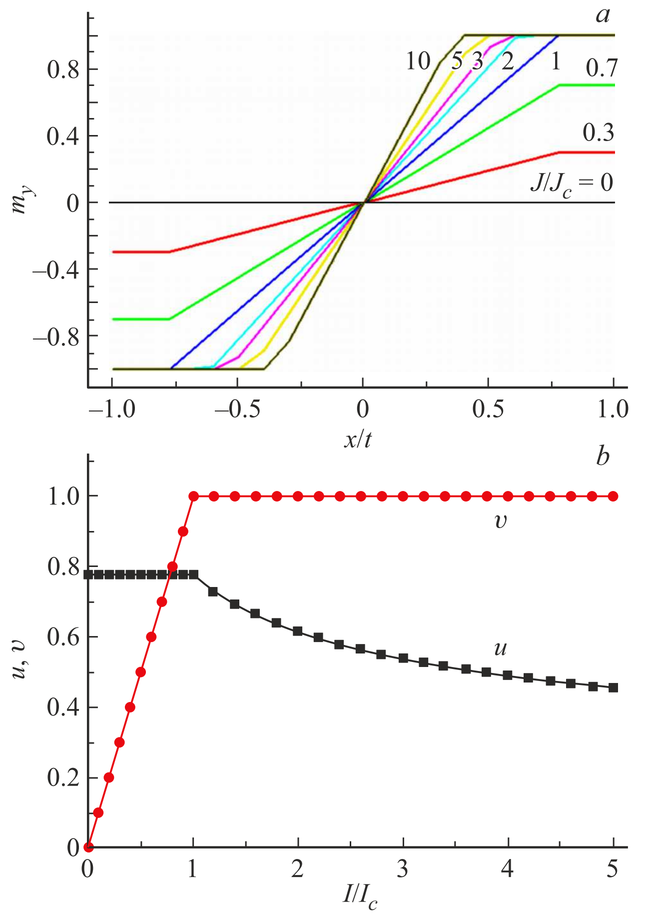

Figure 1. Evolution of the exchange spring with increasing current. *a* is magnetization profiles over the film thickness at $j/j_c = 0$ (black line), 0.3 (red), 0.7 (green), *1, 2, 3, 5* and *10*. *b* is dependence of the parameters u and v (half-width and amplitude of the exchange spring) on the magnitude of the current.

As before, it can be estimated using equation (1), now understanding by x the half-thickness of the additional layer, and by j — the current density in it. The general expression for the field is modified from expression (1) to

$$H_y(x) = (2\pi/5)j(x + \varepsilon t_1), \tag{11}$$

where $\varepsilon = j_1/j$ is the ratio of the current densities in the additional and main layers. It is easy to see that the position of the field node shifts from $x = 0$ to $x = -a = -\varepsilon t_1$ regardless of the current value. It is natural to assume that the node of the exchange spring will be located at the same point. Assuming the previous linear approximation (2) in the region $|x + a| \le u$ and repeating the already known process of energy minimization, we obtain instead of expressions (5)–(7)

$$u = \left((3/5)(t^2 + \varepsilon^2 t_1^2)\right)^{1/2}, \tag{12}$$

$$v = 2\pi M j(25A^{-1})\left((3/5)(t^2 + \varepsilon^2 t_1^2)\right)^{3/2}, \tag{13}$$

$$j_c = 25A(2\pi M)^{-1}\left((3/5)(t^2 + \varepsilon^2 t_1^2)\right)^{-3/2}. \tag{14}$$

At $\varepsilon = 0$, the expressions (12)–(14) go over to the corresponding equations (5)–(7) for a single layer. The new distribution of magnetization in the ferromagnetic layer is shown in Fig. 2, *a*. It can be seen that the structure of the exchange spring itself has changed insignificantly, but now it is shifted as a whole towards the nonmagnetic layer. Despites the magnitude of the additional field may be relatively small, this displacement plays an important role in controlling the energy stored in the exchange spring.

Let's consider, for example, the total transverse magnetization along the y axis. In the case of a single ferromagnetic layer, it is obviously equal to zero due to the symmetry of the field with respect to the middle plane of the film. However, in the presence of a second current-carrying layer, this magnetization is nonzero:

$$\langle m_y \rangle = \frac{1}{2t} \int_{-t}^{t} m_y(x)dx = av/t. \tag{15}$$

Together with the value of v, the transverse magnetization increases linearly with current, reaching saturation above the critical value j_c (Fig. 2, *b*). It usually remains less than one even in saturation due to the smallness of the

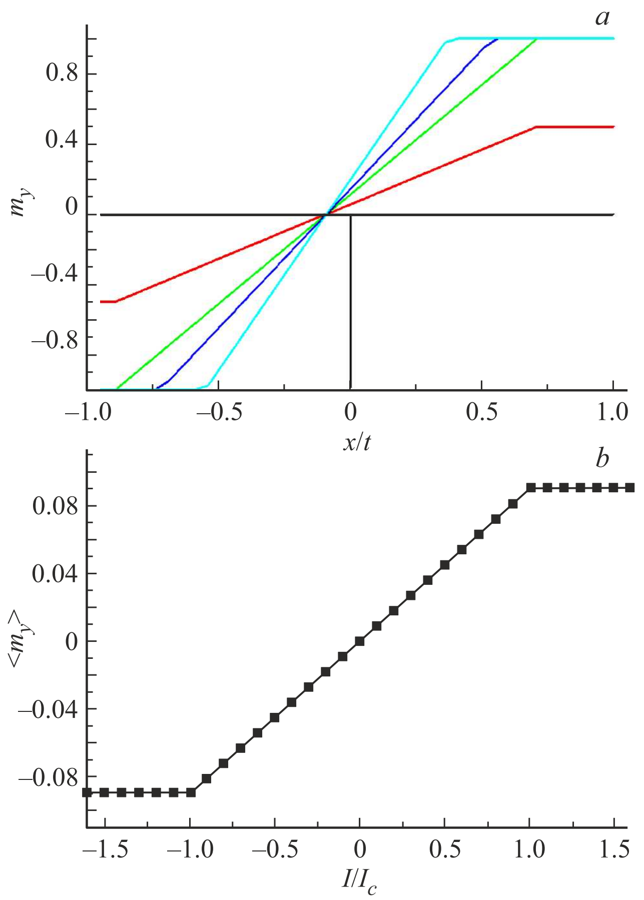

Figure 2. *a* — magnetization profiles in the ferromagnetic layer of a two-layer system. The designations are the same as in Fig. 1. *b* is dependence of the average value of the lateral relative magnetization $\langle m_y \rangle$ on the flowing current.

parameter a, but the effect is nonzero for any geometrical parameters of the layers. At present, current-induced transverse magnetization is most often interpreted as a manifestation of the spin Hall effect [32,33]. The deviation of the average magnetization due to the asymmetry of the magnetic field, as a rule, is not taken into account. However, it seems possible that at least part of the experimentally measured „spin current" has a completely various nature, as described above. In particular, this contribution does not depend on the spin polarization of the carriers and remains unchanged even in the case of a completely unpolarized current.

Another manifestation of the asymmetry of the current field of a two-layer system is that the gain in energy relative to the initial zero state now gives not only the exchange spring, but also the state of uniform magnetization across the wire. Substituting into equation (3) the expression for the field (11) and $m_y \equiv 1$ leads to the result

$$W = -(4\pi/5)Mj\varepsilon t t_1. \qquad (16)$$

The energy of a homogeneous state with transverse magnetization turns out to be linear in the current, while the energy of the exchange spring is quadratic in j. This means that at very low currents the homogeneous transverse state is more favorable, and as the current increases, a phase transition to the state with an exchange spring should occur (Fig. 3). In real samples, this transition is apparently smoothed out by the presence of demagnetization fields and the vertical component of the current field. To elucidate this issue, a more precise analysis is required, but it is noteworthy that even in our simplified model, the question of the ground state of magnetization in the presence of a current turns out to be nontrivial.

Hitherto, we have considered as the ground state (in the absence of current) a uniformly magnetized ferromagnetic layer. Let's now show that the field asymmetry in two-layer systems can also affect the behavior of domain walls. Let's consider the well-known phenomenon of domain wall bending under the action of an inhomogeneous current field [18–21]. Figure 4, *a* shows a domain wall separating two domains of opposite polarity (here, the presence of the corresponding magnetic anisotropy is assumed). When a current is passed, the wall is deformed, since the field on both sides of the sample has a various sign and pushes the wall in opposite directions. The exact solution for the shape of the deformed Bloch wall was obtained by several authors [18–21]; for our purposes, we may not specify the structure of the wall, assuming only that it has a certain surface energy σ and tilts at an angle θ determined by the energy's balance

$$W/2 = \frac{\sigma t}{\cos\theta} - \frac{(2\pi/5)jMt^3\tan\theta}{3}. \qquad (17)$$

Here, the increase in the surface energy is compensated for by the favorable orientation of the magnetization in triangular regions. Minimizing this expression, we obtain the equilibrium angle

$$\sin\theta = \frac{(2\pi/5)jMt^2}{3\sigma}. \qquad (18)$$

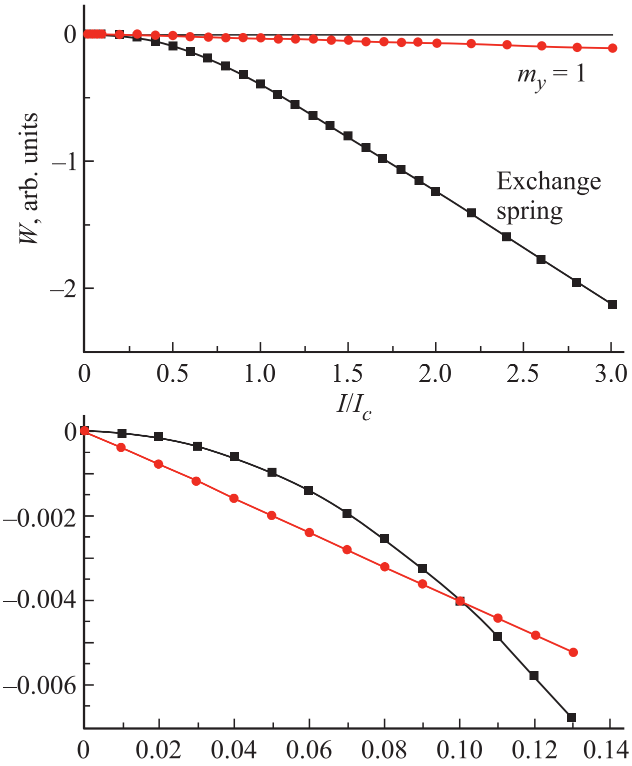

Figure 3. The energy of the state with an exchange spring (black squares) and the uniform transverse state (red circles) depending on the magnitude of the current in a two-layer system. At the bottom is enlarged initial part of the diagram.

This value differs from the exact result [18–21] only by a numerical factor of the order of one. The angle of inclination increases as the current increases, leading to an abrupt reorientation of the wall when a certain critical current is reached. When the current is turned off, the second term in equation (17) vanishes, and the wall elastically returns to its original position, straightening around its center of symmetry.

In the presence of an additional current-carrying layer, the magnetic field node, as we already know, is displaced from the mean plane of the ferromagnetic film. Therefore, the domain wall experiences excess pressure on one of the sides and moves further here than on the opposite side (Fig. 4, *b*). In the center of the wall, this displacement will be $q = a \cdot \tan\theta$. When the current is suddenly turned off, the wall rotates back around its „center of gravity", so that its position remains stationary. Therefore, in this case, after a current pulse, the wall will acquire a residual displacement q. In the experiment, this will manifest itself as the advance of the wall along the sample with an

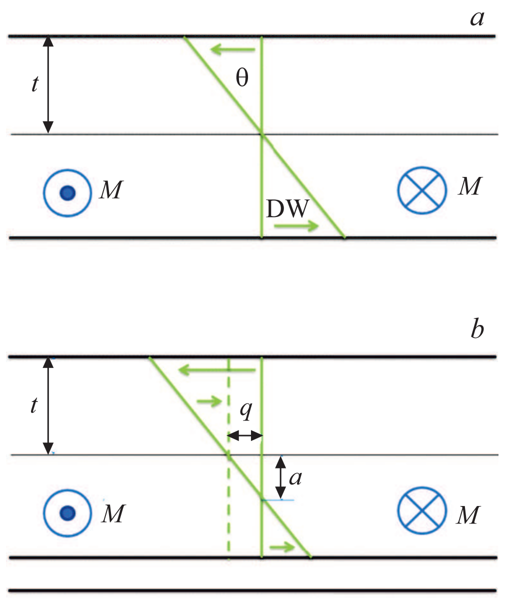

Figure 4. Deformation of the domain wall (green line) under the action of inhomogeneous magnetic fields created by the flowing current. a — in a single ferromagnetic layer, the advancing field component has a various sign at the edges of the sample, displacing the wall in opposite directions. When the current is turned off, the surface energy of the wall returns it to its original position. b — in the presence of an additional current-carrying layer, the field is asymmetric (the field node is in position a), and the wall displacement is greater at one of the edges than at the other. After the termination of the action of the current pulse, the new position of the wall does not coincide with the initial one, leading to a finite displacement q.

apparent speed

$$V = \frac{2\pi M t^2 a}{15\sigma\tau}\, j, \tag{19}$$

where τ is current pulse duration. Expression (19), which is true at a current density much lower than the critical value, formally describes the current-linear dynamics of the domain wall, the mechanism of which, as in the case of the pseudo-Hall effect, has nothing to do with the assumed spin polarization of current carriers.

Over the past decades, an exceptionally large array of experimental data has been accumulated on the interaction of the magnetization of a ferromagnetic layer with electric current [34–43]. Particular attention is paid to two areas: the actual transport properties of layered systems and the motion of domain walls. In most works, specific interactions at the interface, which determine the spin characteristics of current carriers, or the individual transfer of angular momentum by individual transport charge carriers, are considered as the driving mechanism of the observed phenomena. The direct effect of the magnetic fields that exist in the vicinity of a ferromagnet, both due to the presence of magnetostatic poles and the global field created by the current (now often called as the Oersted field), is usually considered insignificant. Nevertheless, in many situations, static and dynamic magnetic fields can make a certain contribution to the measured macroscopic quantities, and in the early stages of research, this mechanism was entirely considered as the unique one [18–20].

To understand the role of magnetic fields in spintronics, let us make some simple estimates. In a typical ferromagnet with a saturation magnetization of the order of 1000 G and an exchange length 5 nm, the expected critical current density corresponding to a fully developed exchange spring is $8 \cdot 10^9$ A/cm^2 by the formula (7) for a single ferromagnetic layer thickness of 10 nm. This is much higher than the experimentally measured threshold values of the current causing the motion of domain walls in thin films (usually from 10^8 A/cm^2). However, the critical current decreases rather rapidly (inversed cubic term) with increasing film thickness, reaching the required order of magnitude already at 40 nm. Moreover, according to formula (14), the critical current density decreases in the presence of additional current-carrying layers, the number of which in modern experiments is quite large. Despite the implied relatively small value of currents (and the fields generated by them) in such „technical“ layers, they simply by virtue of their existence shift the exchange spring in the main layer, thereby producing an unequal effect on the surfaces of the ferromagnet. It should also be noted that in the presence of domain walls, magnetization reversal processes proceed much more easily than in a uniformly magnetized material („Brown's coercive force paradox“), and only partial development of the exchange spring is required to rearrange the structure of the boundaries. In any case, the role of the global field cannot be neglected even if it is small, and the spatial redistribution of magnetization should be evaluated separately in each particular case.

Another common objection to the global field is change of its sign in various parts of the sample, which balances the forces acting on the conduction electrons or the domain wall. The above consideration shows that this argument is valid only in the simplest, completely symmetrical situations. The presence of two components of the magnetic field leads to the fact that any asymmetry (for example, the presence of adjacent layers) initiates mechanisms similar to those shown in Fig. 4. (The exact calculation of such phenomena is rather complicated due to the three-dimensional nature of the problem). The residual displacement of the domain wall after its deformation under the action of a current pulse was repeatedly observed experimentally [34–44], but at that time the asymmetry mechanism was not clear, which led to the rapid development of the concept of „electron pressure“ [45]. The mechanism proposed in this article automatically explains many experimentally observed features, for example, the presence of a current threshold, the stochasticity of the wall displacement, the rearrangement of the wall from transverse to longitudinal, the generation of new boundaries, etc. [34–44]. As for the numerical values, the estimate by formula (19) gives a greatly underestimated relative to the experimental value of the velocity of the order of 1 m/s. However, it should be taken into account that this formula is valid only in the linear mode at small tilt angles; as the current increases further, the angle approaches 90°, and the wall mobility grows irreversibly.

In this article, we consider the evolution of the transverse structure of magnetization in a ferromagnetic film under the action of a magnetic field of a current flowing through it. We did not aim to create an exact theory, confining ourselves to a simplified assessment of the expected type of transition structure, as well as the factors that determine the critical values of the current density. If a complete theory is needed, it obviously must combine calculations of the form [24] with the ideas proposed in our article. Numerical micromagnetic simulating of each specific experiment could also become an alternative, but the general principles of the phenomenon are much easier to demonstrate on a simple model. The twisting of the magnetization near the film surfaces leads to the formation of a transition structure of the exchange spring type. Two stages in the evolution of this region with increasing current consist in an increase in the angle at a constant width and further compression with localization in the middle plane of the film. In the presence of adjacent conductive layers, the exchange spring becomes asymmetric, causing the appearance of a nonzero lateral magnetization that increases with current. In the presence of domain walls, the asymmetry of the field induced by the current leads to their advancement along the wire. All of these phenomena exist to some extent for any nonzero current and do not depend on its spin polarization. This should be taken into account when studying the dynamics of domain walls, as well as kinetic transport spin effects.

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Conflict of interest

The author declares that he has no conflict of interest.

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