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A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) was held on November 28, 2007 in the conference hall of the P N Lebedev Physical Institute, RAS. The following reports were presented at the session:

(1) **Gulyaev Yu V, Zil'berman P E, Epshtein E M** (Institute of Radioengineering and Electronics, RAS, Moscow – Fryazino) "Nano-sized structures incorporating ferromagnetic metal layers: new effects due to the passage of a perpendicular current";

(2) **Zvezdin A K, Zvezdin K A, Khvalkovskiy A V** (A M Prokhorov Institute of General Physics, RAS, Moscow) "The generalized Landau – Lifshitz equation and spin transfer processes in magnetic nanostructures".

An bridged version of these reports is given below.

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Nano-sized structures incorporating ferromagnetic metal layers: new effects due to the passage of a perpendicular current

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Over the last decade, the effects caused by a current flowing through a magnetic junction — a nano-sized layered structure comprising contacting ferromagnetic layers — have been actively studied. Particular experimental and theoretical attention is being given to 'spin valve' type structures which consist of three layers: one pinned ferromagnetic layer with a fixed direction of magnetization; one free ferromagnetic layer whose magnetization direction can be varied by an external magnetic field and/or by a passing current, and one nonmagnetic layer closing the electric circuit. The ferromagnetic layers are separated by a thin nonmagnetic spacer which prevents direct exchange coupling between them; the current transport through the spacer is ballistic, diffusive, or tunnel in character. Importantly, the spacer is thin compared to the spin mean free path, implying that the electron spin state is unchanged during the passage of current through the spacer.

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It has been shown experimentally (see, for example, Ref. [1]) that an electric current flowing perpendicular to the layers can cause a jumplike change in the way the magnetization of the free ferromagnetic layer is oriented with respect to that of the pinned one. Specifically, this effect was observed to occur for current densities above a certain threshold value falling in the range of $\sim 10^6 - 10^8$ A cm^{-2} (see, for example, Refs [1, 2]) and consisted in switching the initial antiparallel configuration to the parallel one. The parallel configuration persisted with decreasing the current to zero and reversing the current direction. When the reverse current density reached the above-mentioned threshold value, the system underwent backswitching and returned to the antiparallel configuration. Because the resistance of the magnetic junction depends on the relative orientation of the magnetic layers (whence the well-known effect of giant magnetoresistance), a change in the junction resistance accompanied the switching, resulting in a hysteretic dependence of resistance on current.

Most experimenters standardly rely on the theory developed by Slonczewski [3] and Berger [4] to interpret the observed effects. According to this theory, as the electrons of a spin-polarized current pass through the boundary between two noncollinear ferromagnets, they transfer their spin torque to the magnetic lattice (when an electron enters a medium with a different direction of the spin quantization axis, its transverse spin component — the one perpendicular to this new direction — is lost to the lattice). In reality, however, even if the ferromagnetic layers are initially collinear, this collinearity is continuously violated by fluctuations. At a sufficiently high current density, the fluctuations become unstable, and their buildup leads to the free-layer magnetization reversal. It takes a distance of the order of the Fermi electron wavelength (~ 1 nm) from the boundary for the transverse component of the electron magnetization to relax.

An alternative mechanism for how a spin-polarized current affects the configuration of a magnetic junction was suggested in Refs [5, 6] by taking into account the fact that the passage of a current is accompanied by the injection of nonequilibrium spins from the pinned to the free layer. As a result of this, regions of nonequilibrium spin polarization appear near the boundaries between these layers, as well as between the free layer and the nonmagnetic layer, whose widths are determined by the spin diffusion length and are an order of magnitude greater than the relaxation length of the transverse magnetization component. Due to the sd-exchange interaction between the electrons and the magnetic lattice, the presence of such regions can either decrease or increase the magnetic energy of the junction, depending on the parameters of the magnetic layers and how their magnetizations are oriented. As a result, the initial magnetic configuration may prove to be energetically unfavorable at a sufficiently high current density, leading to a nonequilibrium phase transition with a change in the magnetic configuration of the structure.

To elucidate what the relative roles of the above two mechanisms are when a spin-polarized current produces sd-exchange switching in a magnetic junction, a theory incorporating both mechanisms was developed [7–9]. It was found that in the general case both mechanisms contribute comparably. On the other hand, further studies [10–12] revealed the existence of a strong injection regime, in which the injection mechanism becomes the dominant one, and new effects — such as the irreversible switching from a parallel to antiparallel configuration, the occurrence of a noncollinear stationary state, and the inverse population of spin subbands — become possible. Therefore, although typical, it is by no means always true that the forward-directed current (spin-polarized electrons flowing from the pinned to the free layer) switches the antiparallel configuration to the parallel one and that the oppositely directed current acts the other way round.

By studying the dependence of the injection level on boundary conditions for a nonequilibrium electron spin polarization it was shown [13] that the injection level depends on the so-called spin resistance Z of the layers, defined as $Z = \rho l/(1 - Q^2)$, where ρ is the resistivity, l is the spin diffusion length, and Q is the degree of conduction spin polarization. When spin-polarized current flows through the contact of two layers, it is primarily in the lower-Z layer where spin equilibrium is violated, so that if the chosen free-layer material has lower spin resistance compared to the neighboring — pinned and nonmagnetic — layers, then pinned-to-free layer spin injection will be effective and that at the exit from the free ferromagnetic layer it will be suppressed. This leads to a large increase in the free-layer nonequilibrium spin polarization and a corresponding reduction in the threshold current density. The instability threshold can be reduced by an estimated two to four orders of magnitude, with the result that the spin torque produced by the current has little or no effect on the magnetic junction [3, 4].

Because there is no contribution from the spin torque, the energy approach can be applied to see what stationary states can be produced in the course of developing instability. This approach is entirely equivalent to — but easier to grasp than — the dynamic scheme based on the solution of the Landau–Lifshitz–Gilbert equations.

The energy U of a magnetic junction has four terms: the Zeeman energy in an external magnetic field H; the energy of the demagnetization field; magnetic anisotropy energy, and the sd-exchange interaction energy between the magnetic lattice and the conduction electrons. In a free layer that is thin compared to both the spin diffusion length and the domain wall thickness, the nonequilibrium spin polarization and the lattice magnetization are constant over the thickness of the layer. Calculations for such a layer yield the following expression for the magnetic energy per unit area:

$$U = 4\pi M^2 L \left\{ -h\hat{M}_z - \frac{1}{2} h_a \hat{M}_z^2 + \frac{1}{2} \hat{M}_x^2 - \frac{j}{j_1} \frac{(Z_1/Z_2)\hat{M}_z + (b/\lambda)\hat{M}_z^2}{(Z_1/Z_3) + \hat{M}_z^2} \right\}, \tag{1}$$

where M is the saturation magnetization, $h = H/4\pi M$, $h_a = H_a/4\pi M$, H_a is the anisotropy field, $\hat{\mathbf{M}} = \mathbf{M}/|\mathbf{M}|$ is a unit vector in the magnetization vector direction, $j_1 = 4\pi elM/(\mu_B \alpha\tau Q_1)$, l is the spin diffusion length, τ is the longitudinal spin relaxation time, α is the sd-exchange interaction constant (all the above quantities refer to the free layer), e is the electron charge, μ_B is the Bohr magneton, L is the free layer thickness, Q_1 is the spin polarization of the pinned layer conduction, $\lambda = L/l$, Z_1, Z_2, Z_3 are the respective spin resistances of the pinned, free, and nonmagnetic layers, and the parameter b describes the relative amount the pinned layer contributes to the sd-exchange interaction energy. The external magnetic field as well as the anisotropy and magnetization of the pinned layer are directed along the z-axis, while the current flows along the x-axis perpendicular to the magnetic junction plane. Formula (1) refers to the case of a forward current flowing in the direction $1 \to 2 \to 3$ and is modified for a reverse current by making the replacement $\hat{M}_z \to (\hat{M}_z)^{-1}$ in the last term in the curly brackets on the right-hand side. The stable stationary state corresponds to the minimum of the magnetic energy.

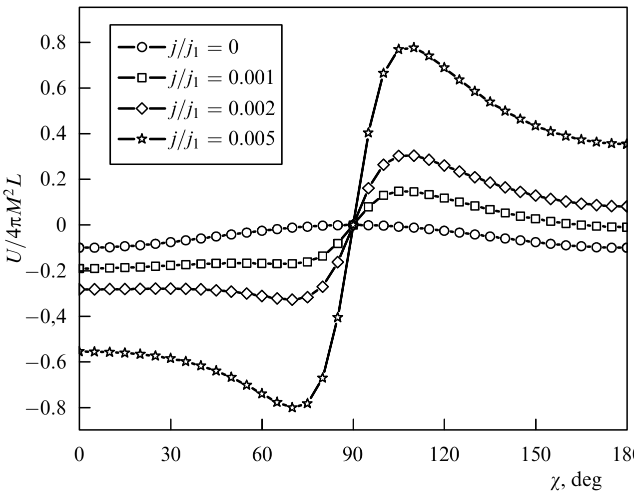

Figure 1. Magnetic energy vs relative orientation of ferromagnetic layers for forward current ($H = 0$, $H_a/4\pi M = 0.2$, $b = 1$, $\lambda = 0.1$, $Z_1/Z_2 = 100$, and $Z_1/Z_3 = 0.1$).

Figure 1 depicts the dependence of the energy on the angle $\chi = \arccos \hat{M}_z$ between the magnetization vectors of the free and pinned layers for $Z_3 \gg Z_1 \gg Z_2$ and different values of the forward current density. At a certain current density, along with the stable stationary states $\chi = 0$ and $\chi = \pi$, a stationary noncollinear state appears in the region $0 < \chi < \pi/2$, which is separated by a potential barrier from the state with $\chi = 0$. At the threshold current density $j = j_{th}$, the parallel configuration corresponding to $\chi = 0$ becomes unstable (the minimum turns into a maximum), and the system is switched to a noncollinear state at an angle of $\chi = \chi_1$ (for fixed parameter values $\chi_1 \approx 70°$). Increasing the current further has little effect on the angle χ_1. As the current decreases, the noncollinear state disappears at a current density considerably (about three times) lower than the threshold value, and the system restores its initial parallel configuration. We also assigned negative values to the angles χ and χ_1. Negative χ and χ_1 imply a negative projection $\hat{M}_y$, whereas for positive angles χ and χ_1 this projection is positive. The dependence of the angle χ_1 on the current density is shown in Fig. 2, in which it is seen that over a wide range of current densities the system exhibits the property of multistability, meaning that there are several stationary states

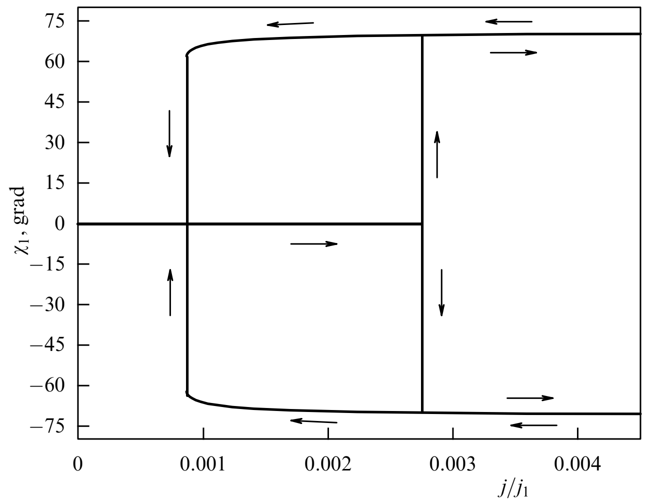

Figure 2. Orientation angle χ_1 of noncollinear state as a function of current density. Structure parameters are the same as in Fig. 1. The arrows indicate changes in the direction of the current.

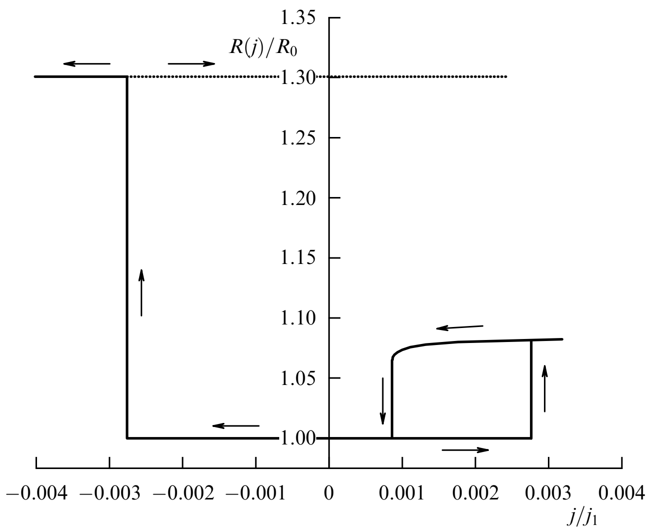

Figure 3. Relative resistance $R(j)/R_0$ versus current density j for a structure in which a noncollinear stationary state is possible for ferromagnetic layers initially oriented *parallel* to one another. Structure parameters are the same as in Fig. 1. It is assumed that $r \equiv R_\pi/R_0 - 1 = 0.3$, where R_0 and R_π are the resistances for the parallel and antiparallel orientations, respectively.

corresponding to one current density value. Exactly which of these materializes depends on the history of how the current has changed over time. Notice that noncollinear states are nonequilibrium ones and they exist only in the presence of a current, so that switching to them is reversible.

As mentioned earlier, the resistance of a magnetic junction depends on the mutual orientation of magnetization in the ferromagnetic layers. Because the appearance of a noncollinear stationary state strongly affects the orientation of magnetization, it should also lead to changes in the resistance of the structure. It is these changes which seem to be the easiest to detect. Figure 3 demonstrates a typical current dependence of magnetization calculated for a structure with $Z_3 \gg Z_1 \gg Z_2$, in which the stationary state arises for layers initially oriented parallel to each other with increasing forward $(1 \to 2 \to 3)$ current. It is exactly this

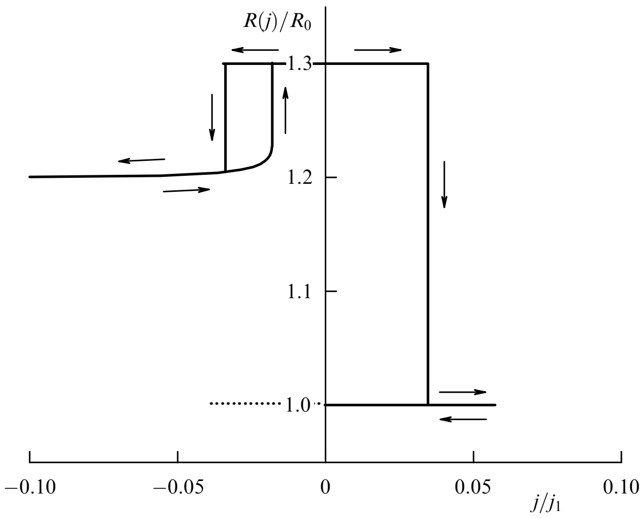

Figure 4. Relative resistance $R(j)/R_0$ versus current density j for a structure which can exhibit a noncollinear stationary state at the initial *antiparallel* orientation of the ferromagnetic layers. Spin resistance ratio $Z_1/Z_3 = 10$, while the remaining parameters of the structure are the same as in Figs 1 and 3.

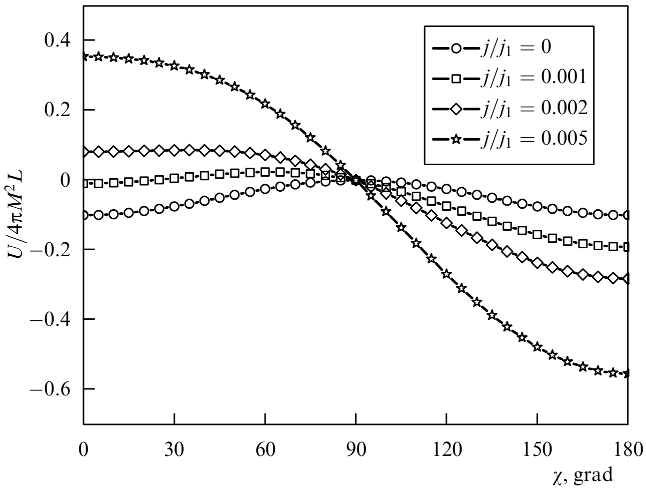

Figure 5. Magnetic energy versus relative orientation of ferromagnetic layers for the case of reverse current. Parameters are the same as in Fig. 1.

situation which is clarified with Fig. 1, in which it is seen that instability of magnetic configuration at the forward current case results in a minimum at an angle of $\chi = \chi_1$.

The other (antiparallel) mutual orientation of the layers also gives rise to a noncollinear stationary state provided that the spin resistances follow a different relation, namely, $Z_1 \gg Z_3 \gg Z_2$, and that a reverse current $(1 \leftarrow 2 \leftarrow 3)$ is increased. This stationary state also leads to current-dependent magnetoresistance (see Fig. 4 for an example).

The initial antiparallel configuration $(\chi = \pi)$, for $Z_3 \gg Z_1 \gg Z_2$, remains stable with increasing current [the function $U(\chi)$ has a minimum at $\chi = \pi$ (see Fig. 1)]. Because in such a configuration the spins injected into the free layer are aligned opposite to their local counterparts, the nonequilibrium spin polarization is negative. Under high-injection conditions $(Z_1, Z_3 \gg Z_2)$, for a current density of $\sim 10^7 - 10^8$ A cm^{-2}, it is possible to achieve a negative total spin polarization (i.e., the spin subbands are inversely populated) — potentially leading to the possibility of inventing terahertz amplifiers and generators relying on transitions between spin subbands (a possibility announced earlier in Ref. [14]).

Figure 5 shows the dependence of the magnetic energy on angle χ for the case of $Z_3 \gg Z_1 \gg Z_2$ and for various values of reverse current density. In this event, the parallel configuration $\chi = 0$ at the threshold current density $j = j_{\rm th}$ (the same as for the forward current) becomes unstable, switching the system to the stable antiparallel magnetic configuration $\chi = \pi$, which is also stable for forward current (see Fig. 1), so that the switching is irreversible. This behavior can be used to magnetically record one-time (archival) information using spin-polarized current. With the sd-exchange interaction with a characteristic length of $\sim 10^{-6}$ cm underlying the process, extremely high recording density can be achieved.

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The generalized Landau – Lifshitz equation and spin transfer processes in magnetic nanostructures

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1. Introduction

Recently, a new method for magnetic-body magnetization reversal has been proposed [1, 2] and experimentally substantiated [3 – 5], based on the fact that a current traversing a magnetic system transfers not only charge but also spin, and constitutes therefore a flux of the angular momentum. Spin polarization of the current (i.e., nonvanishing total spin momentum) arises due to the exchange interaction, for the current flowing through a ferromagnetic. If the current flows from a ferromagnetic to a nonmagnetic material, it retains its polarization over a certain length. However, if the polarized current traverses a nonuniformly magnetized magnetic system, its spin moment has to adjust itself to the system's magnetization. Because spin is locally conserved, the change in the angular momentum of the current is transferred to the ferromagnetic; thus, the divergence in the spin flow gives rise to a torque that acts on the magnetization. Such a process has come to be known as spin transfer. Under certain conditions, the spin transfer can result in the magnetization reversal of magnetic structures, as well as causing spin wave generation and domain wall motion. This effect is quantum in nature and undoubtedly one of fundamental interest.

Adding to the interest in exciting magnetization in this way are the successes achieved and problems encountered in developing MRAM (Magnetoresistance Random Access Memory) elements, microwave devices, and magnetic logic elements [6]. Various aspects of the effect under study were discussed in reviews [6 – 8].

The theoretical description of spin transfer process in nonuniform ferromagnetic media usually relies on the so-called sd-model which assumes that charge and spin currents are carried by external electrons whose (Bloch) wave functions are primarily formed by the s- and p-orbitals of the material's atoms, while the magnetization is determined by the inner underpopulated d-orbitals (for details see Ref. [9]). In this approach, the sp – d hybridization is assumed to be sufficiently small and responsible for the exchange interaction (with the energy on the order of several tenths of an electron-volt) between the sp and d electrons. The corresponding exchange fields are on the order of or higher than 10^7 Oe.

The mechanism by which the current's spin moment (or more precisely, its *transverse* component [1, 2]) adjusts itself to the direction of the local magnetization is the exchange interaction mentioned above, and because of the large value of the exchange field this adaptation process occurs over distances on the order of 1 nm. This distance is much smaller than the characteristic length of spin – lattice relaxation, which is several dozen nanometers in ferromagnetic metals. Thus, the spin flow is not scattered by the impurities, it is only redistributed. The spin flux $\hat{Q}$ is transferred from moving to localized electrons in the form of torque $\mathbf{T}$ which causes their spins to reorient themselves or to precess; $\hat{Q}$ and $\mathbf{T}$ are defined as $Q_{ij} = \sum v_j S_i$, $T_i = -\nabla_j Q_{ij}$, where $\mathbf{v}$ and $\mathbf{S}$ are, respectively, the velocity and spin vectors, the summation runs over all the electrons of the flow, and i, j are the Cartesian indices. The spin-current-induced dynamics of a nonuniformly magnetized s – d system are described approximately by the generalized Landau – Lifshitz equation (GLLE) involving an additional spin torque $\mathbf{T}_{\rm s.t.} \equiv \gamma \mathbf{T}$ (where γ is the gyromagnetic ratio):

$$\frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} = -\gamma \mathbf{M} \times \mathbf{H}_{\rm eff} + \mathbf{T}_{\rm s.t.} + \frac{\alpha}{M_{\rm s}} \left(\mathbf{M} \times \frac{\mathrm{d}\mathbf{M}}{\mathrm{d}t} \right), \tag{1}$$

where $\mathbf{M}$ is the magnetization vector, t is the time, α is the Gilbert damping parameter, $M_{\rm s}$ is the saturation magnetization, and the effective field $\mathbf{H}_{\rm eff}$ [10] sums the contributions from the external magnetic field and the magnetostatic, exchange interaction, and anisotropy fields.

Usually, two configurations of planar structure are employed to consider spin transfer processes. In the first and most widely used CPP (current perpendicular to the plane) configuration, the current flows perpendicular to layers in a structure containing layers with different magnetization directions. In the second, CIP (current in the plane) configuration, the current flows along the magnetic layer containing a domain wall (DW).