05

Influence of spin-orbit interaction on the effect of spin Coulomb drag

© I.I. Lyapilin

M.N. Mikheev Institute of Metal Physics, Ural Branch, Russian Academy of Sciences,
Yekaterinburg, Russia

E-mail: lyapilin@imp.uran.Ru

Received April 18, 2024
Revised April 18, 2024
Accepted May 8, 2024

The influence of spin-orbit interaction (Rashba) induced by spin-orbit interaction dynamics on transport phenomena in spatially heterogeneous magnetic structures is considered. It is shown that the transport phenomena related to the manifestation of spin-dependent electric field lead to the strengthening of the effect of spin Coulomb entrainment of charge carriers.

Keywords: spin current. spin-orbit interaction electron-electron drag.

DOI: 10.61011/PSS.2024.06.58697.30HH

The exchange interaction of s-electrons forming a spin current and localized d-electrons determining the magnetization of the structure $\mathbf{M}(\mathbf{r},t)$ in spatially inhomogeneous conducting magnetic structures is one of the important areas of research in the field of spintronics. Localized spin $\mathbf{S}(\mathbf{r},t)$ is related to magnetization by the ratio $\mathbf{M}(\mathbf{r},t) = (-g\mu/a^3)\mathbf{S}(\mathbf{r},t)$ (a — lattice constant, g — factor, μ — Bohr magneton). The spin electron ideally follows the direction of the magnetization vector $\mathbf{M}(\mathbf{r},t)$ in the limit of an infinitely large exchange field. In reality, there is some misalignment and associated spin relaxation, which is described phenomenologically by introducing the dissipative term R into the Landau−Lifshitz−Gilbert equation describing the evolution of magnetization.

The local unitary transformation $U(\mathbf{r},t)$, rotating the spin space in a direction parallel to the inhomogeneous local magnetization $\mathbf{M}$(**r**,t), diagonalizing the exchange interaction $U(\mathbf{r},t)^\dagger(\mathbf{m}(\mathbf{r},t)\boldsymbol{\sigma})U(\mathbf{r},t)$, generates spin-dependent potentials $\mathbf{A}$(**r**,t) forming spin-dependent $\mathbf{E}_s(\mathbf{r},t)$, $\mathbf{B}_s(\mathbf{r},t)$ electromagnetic („concomitant") fields [1]. These fields cause spin-motive Lorentz forces $\mathbf{F}_s(\mathbf{r},t)$ acting on s-electrons resulting in the realization of new physical effects [2]. Thanks to the latter, it becomes possible to transfer energy between the spin subsystems of conducting and localized electrons, at the same time the magnetic energy stored by the magnetization of the crystal can be converted into an electric voltage. Spin electromagnetic fields $\mathbf{E}_s(\mathbf{r},t)$, $\mathbf{B}_s(\mathbf{r},t)$ realize an additional energy dissipation channel and cause the movement of the domain wall [3].

Expressions for spin electromagnetic fields $\mathbf{E}_s(\mathbf{r},t)$, $\mathbf{B}_s(\mathbf{r},t)$, written through angles $(\theta(\mathbf{r},t),\phi(\mathbf{r},t))$, defining the space-time profile of local magnetization

$$\mathbf{M}(\mathbf{r},t) = \\ = \mathbf{m}\big(\sin\theta(\mathbf{r},t)\cos\phi(\mathbf{r},t),\ \sin\theta(\mathbf{r},t)\sin\phi(\mathbf{r},t),\ \cos\theta(\mathbf{r},t)\big),$$

have the following form [1,4,5]:

$$E_{si} = s\,\frac{\hbar}{2e}\,\mathbf{m}(\partial_t\mathbf{m}\times\partial_i\mathbf{m}),$$

$$B_{si} = -s\,\frac{\hbar}{2e}\,\varepsilon_{ijk}\,\mathbf{m}(\partial_j\mathbf{m}\times\partial_k\mathbf{m})_i,\ \ s=\uparrow,\downarrow.$$

Here $\mathbf{m}$ is a unit vector directed along the magnetization. $(\uparrow,\downarrow)$ — characterize the direction of the electron spin. $\partial_t = \partial/\partial t$, $\partial_i = \partial/\partial x_i$, ε_{ijk} — the single Levy−Civita tensor.

Spin electromagnetic fields are caused by both time variables and spatially inhomogeneous magnetization regions $\mathbf{M}(\mathbf{r},t)$. The force generated by these fields is also spin-motive (SMF) and is similar to the Lorentz force

$$\mathbf{F}_s(\mathbf{r},t) = e\big(\mathbf{E}_s(\mathbf{r},t) + \mathbf{v}_s\times\mathbf{B}_s(\mathbf{r},t)\big).$$

The manifestation of spin-motive force is a universal phenomenon in magnetic metal. The concept of SMF was discussed both for non-magnetic materials under conditions of inhomogeneous magnetic fields [6], for ferromagnets [4,7], including the spin-orbit interaction and can be understood on the basis of gauge field theory, the equation of motion and the Berry's spin phase [6,8].

Spin-dependent fields, although small in magnitude, are nevertheless observed experimentally [3]. They are related to the spin polarization of conduction electrons $P = (n^\uparrow - n_\downarrow)/(n^\uparrow + n_\downarrow)$. The polarization of conduction electrons characterized by the value P is determined by the type of the initial magnetic material in ferromagnetic metals and is of the order of 0.3−0.8. In this case, the macroscopic electron drift $(\uparrow,\downarrow)$ caused by the spin field $\mathbf{E}_x(\mathbf{r},t)$ results in the realization of the spin current $J_s = PJ_e$ (J_e — charge current).

The spin fields $\mathbf{E}_s(\mathbf{r},t)$, $\mathbf{B}_s(\mathbf{r},t)$ affect the kinetics of conduction electrons. As follows from the expression (1) the spin field $\mathbf{E}_s(\mathbf{r},t)$ shifts electrons with spins $(\uparrow,\downarrow)$ in opposite directions, thereby inducing spin-polarized current J_s

unlike the constant electric field $\mathbf{E}_O$, which does not feel the spin state of the charge carrier.

The action of the magnetic component of the spin-driving force $\mathbf{E}_s(\mathbf{r}, t)$ is also unusual. Unlike the usual magnetic field $\mathbf{B}_O$, which affects only the charge of the carrier, the spin magnetic field $\mathbf{B}_s(\mathbf{r}, t)$ deflects free charge carriers depending on the orientation of the spin in opposite directions, thereby inducing Hall voltage and spin current if electron concentrations $(n^{\uparrow} \neq n^{\downarrow})$.

Therefore, the electric and magnetic components of the spin fields select free charge carriers in the spin direction. The system of conduction electrons can be considered as consisting of two spin subsystems in this case, each of which is characterized by its own spin direction. The electron drift velocities in each of the spin subsystems will be spin-dependent since the drift velocity of charge carriers is mainly due to the influence of an electric field. As a result, this leads to the realization of conditions under which the effects associated with the interaction of charge carriers in different spin subsystems become possible. One of these interactions is the Coulomb interaction of charge carriers, which plays a leading role in various phenomena. The impact of electron-electron interactions on transfer phenomena in systems of various dimensions is an area of active experimental and theoretical studies. However, both the magnitude and the impact of the Coulomb interaction on the kinetic properties of crystals are difficult to measure.

One of the methods that has shown its efficiency in measuring the scattering velocities directly due to the Coulomb interaction is the effect of Coulomb drag (CD) of charge carriers [9,10] The effect constitutes the occurrence of a response in the form of a voltage (or electric current) in a conductive system when passing current through another conductive film, separated from the first by a dielectric layer. The effect is based on the interlayer Coulomb interaction of conduction electrons separated by a dielectric. A quantitative measure of CD in the case of two conductive layers separated by a dielectric is the entrainment resistance (transresistivity) [11]. The manifestation of the CD effect of charge carriers is also possible in a system of spin-polarized charge carriers.

Let's consider the conductivity of carriers with different spins in the framework of a two-channel model (conductivity through two spin channels with different spin orientation in each channel). Assuming that the drift velocities of the carriers $\mathbf{v}^{\uparrow}, \mathbf{v}_{\downarrow}$ in each of the spin subsystems attributable to the spin field $\mathbf{E}_s$ are different. In this case, the Coulomb interaction, while maintaining the full momentum of the system, will redistribute it between charge carriers in various spin channels in the absence of other sources of electron scattering. At the same time, faster carriers, transferring part of the momentum to the slow ones, will drag them, thereby realizing the effect of spin Coulomb drag (SCD) [12].

Thus, a local change of magnetization in inhomogeneous magnetic structures, inducing a spin electromagnetic field, naturally implements the conditions necessary for the manifestation of the effect of spin Coulomb drag. Microscopic description and analysis demonstrated [12] that Coulomb drag of spin-polarized carriers in low temperature range results in a change of the relaxation frequency of the electron pulse Ω_p when the main source of scattering of the electron momentum inside each spin subsystem is the scattering of charge carriers at randomly located impurity centers ω_{ei} and electron-electron scattering ω_{ee}, which is determined by the expression

$$\Omega_p = \omega_{ei}\omega_{ee}/(\omega_{ei} + \omega_{ee}).$$

As we have already noted above, the spin electromagnetic fields are small, although they are observed experimentally (detected by measuring the spin current). Therefore, it is quite appropriate to search for interactions acting as „amplifiers“ effects caused by the action of these fields. It is shown in Ref. [13] that a spin-motive force can be generated due to a time-varying electric field $\mathbf{E}(t)$ and $\mathbf{E}_s \sim (\mathbf{m} \times \partial\mathbf{E}/\partial t)$ in a system with static and homogeneous magnetization and spin-orbit interaction.

The issue related to the time dependence of the spin electric field also needs to be solved. Its average is zero with a periodic dependence of the amplitude of the electric field on time. Therefore, it is necessary to solve this problem for manifestation of the effects caused by the spin field.

Let us consider the spin-orbit interaction as one of the possible „amplifiers“ of the action of the spin field $\mathbf{E}_s$ which is realized when the structural inversion symmetry is upset [14]. Experiments with thin magnetic layers with strong structural inversion asymmetry have shown the presence of large effective magnetic fields [15], the dynamics of magnetization in which can induce a large spin current. It is obvious that the Rashba spin-orbit interaction (RSOI) and the additional spin precession induced by this interaction should have an impact on the formation of spin fields. It should be noted that the use of RSOI as one of the possible methods for generating spin current in a two-dimensional electron gas is also due to the fact that in this case additional generation amplification should be expected, due to the time dependence of the RSOI constant due to the possibility of changing the gate voltage. The Rashba spin-orbit interaction is described by the Hamiltonian

$$H_R = (\alpha_R(t)/\hbar)(p_x\sigma_y - p_y\sigma_x) = (\alpha_R(t)/\hbar)(\boldsymbol{\sigma} \times \mathbf{p})\mathbf{n},$$

$\alpha_R(t)$ — RSOI constant. $\boldsymbol{\sigma}$, $\mathbf{p}$ — Pauli matrices and electron momentum $\mathbf{n}$ — unit vector.

The effective electric field attributable to the RSOI can be found using a standard method by applying the unitary transformation [1] $U(\mathbf{r}, t)$ to the Rashba Hamiltonian. The spin electric field $\mathbf{E}_s$ realized in this case can be represented as the sum of two terms: the first of which is due to the spatio-temporal change of magnetization

$$\mathbf{E}^R_{1i}(\mathbf{r}, t) = \alpha_R(t)m_e/(\hbar/e)(\partial_t\mathbf{m} \times \mathbf{n})_i,$$

and the second term is associated with the possibility of temporarily changing of the RSOI constant

$$\mathbf{E}^R_{2i}(\mathbf{r},t) = \alpha_R(t) m_e/(\hbar/e)(\mathbf{m}\times\mathbf{n})_i,$$

(m_e — electron mass). The possibility of changing the constant $\alpha_R(t)$ by changing the gate voltage, allows for a significant control of the magnitude of the field and SMF.

Comparison estimates show that the magnitude of the spin field with parameters characteristic of the Pt/Co(0.6 nm)/AlO [15] compound increases the spin-motive force by more than an order of magnitude in comparison with the spin field $\mathbf{E}_s$, thereby improving the possibility of observations of the effect of SCD. The field $\mathbf{E}^R_{2i}(\mathbf{r},t)$ makes an additional contribution to SMF. The problem associated with the time dependence of the Rashba spin field can be solved by rectification of the negative component of the spin electric field component. A unidirectional (positive), time-varying electric field is obtained as a result. The rectification effect in this case is similar to the diode effect [16].

Acting as an „amplifier“ the spin-orbit interaction of the Rashba results in a significant increase of the spin electric field, and therefore in an increase of the spin-motive force, which ultimately manifests itself in an increase of the effect of spin Coulomb drag of spin-polarized charge carriers due to electron-electron (Coulomb) interaction.

Funding

The work was performed within the framework of the state assignment of the Ministry of Education and Science of the Russian Federation (topic „Spin“, No. 122021000036-3).

Conflict of interest

The author declares that he has no conflict of interest.

References

[1] G.E. Volovik. J. Phys. C **20**, L83 (1987).
[2] S.A. Yang, Geoffrey S.D. Beach, C. Knutson, Di Xiao, Zh. Zhang, M. Tsoi, Q. Niu, A.H. MacDonald, J.L. Erskine. Phys. Rev. B **82**, 054410 (2010).
[3] S.A. Yang, G.S.D. Beach, C. Knutson, D. Xiao, Q. Niu, M. Tsoi, J.L. Erskine. Phys.Rev. Lett. **102**, 067201 (2009).
[4] Yu. Yamane, J. Ieda, J. Ohe, S. Barnes, S. Maekawa. J. Appl. Phys. **109**, 07C735 (2011).
[5] J. Ohe, S. Maekawa. J. Appl. Phys. **105**, 07C706 (2009).
[6] A. Stern. Phys. Rev Lett. **68**, 1022 (1992).
[7] J. Ieda, Y. Yamane, S. Maekawa. SPIN **3**, 1330004 (2013).
[8] M.V. Berry. Proc. R. Soc. London A **392**, 45 (2013).
[9] A.G. Rojo. J. Phys. Condens. Matter **11**, R31 (1999).
[10] B.N. Narozhny, A. Levchenko. Rev. Mod. Phys. **88**, 025003 (2016).
[11] A.-P. Jauho, H. Smith. Phys. Rev. B **47**, 4420 (1993).
[12] I.I. Lyapilin. FMM **124**, *8*, 795 (2023).
[13] S.-Q. Shen. Phys. Rev. Lett. **95**, 287203 (2005).
[14] A. Bychkov, E.I. Rashba. JETP Lett. **39**, 78 (1984).
[15] J. Pizzini, I.M. Miron, G.S. Auffret, B. Rodmacq, A. Schuhl, S. Vogel, P. GambardellaI. Nature Mater. **9**, 230 (2010).
[16] B. Miller, D.M. Zumbul, C.M. Marcus, Y.B. Lyanda-Geller, D. Goldhaber-Gordon, K. Campman, A.C. Gossard. Phys.Rev. Lett. **90**, *7*, 076807 (2003).

Translated by A.Akhtyamov