Metamagnetic transition self-propelled by spin injection

A. A. Zyuzin and A. Yu. Zyuzin
A.F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia
(Received 7 July 2010; published 27 October 2010)

We study metamagnetic phase transition of itinerant electrons controlled by the spin-injection mechanism. The current flow between a ferromagnetic metal and a metamagnetic metal produces the nonequilibrium shift of chemical potential for spin-up and spin-down electrons. This shift acts as an effective magnetic field driving the metamagnetic transition between low and high magnetization states of the metamagnet in the vicinity to the contact with the ferromagnet. We show that high magnetization state of the metamagnet self propels into the bulk of the metamagnet and the length of this state has threshold dependence on the electrical current.

DOI: 10.1103/PhysRevB.82.134445 PACS number(s): 72.25.Hg, 75.30.Kz

I. INTRODUCTION AND MAIN RESULTS

The idea of the spin injection from ferromagneic metal to paramagnetic (p) metal was first proposed by Aronov.[1] In the spin-injection process the charge-current flow between ferromagnetic and paramagnetic metals produces the nonequilibrium magnetization in the paramagnet. This magnetization is proportional to the induced chemical potentials difference of electrons with opposite spins[1]—the spin accumulation. Nonequilibrium spin imbalance due to injection was observed by Johnson and Silsbee.[2] The theory of spin injection was developed in details in many works[3–7] and well-studied experimentally, see for a review Refs. 8 and 9. However, the degree of electron spin polarization is relatively small at standard spin injection from ferromagnetic to paramagnetic metal.[10,11] In order to increase the nonequilibrium polarization it is interesting to look for the possibility of spin-injection-based magnetic transition in metamagnetic metals. Here we consider the metamagnetic transition of itinerant electrons induced by the spin-injection mechanism. Let us briefly describe the properties of the metamagnet.[12,13] When the energy splitting of electrons with opposite spins is smaller than the characteristic energy scale of itinerant electrons, then magnetic part of the free-energy density can be expanded in powers of magnetization $F(H,M)=aM^2+bM^4+cM^6-MH$, where coefficients a,b,c are determined by the energy dependence of the density of states at the Fermi level, H is the external magnetic field and M is the magnetization.

At $b<0$ magnetic part of free energy $F(H=0,M)$ might have extremum at nonzero $|M|$ as it is shown in Fig. 1, which schematically illustrates evolution of free energy with increasing magnetic field due to contribution of the term $-MH$. At small magnetic field the state with low magnetization (LM) has lower energy while at magnetic field larger than so-called metamagnetic field H_{m} the metamagnetic state acquires lower energy and system undergoes to state with high magnetization (HM). Metamagnetic state is induced by external magnetic field through the first-order phase transition.[12,13]

Metamagnetic transition of itinerant electrons might appear[12,13] in strongly enhanced Pauli paramagnets when the Fermi level is close to peak in electron density of states. In this case Zeeman splitting increases the density of states and drives the metamagnetic transition.

The chemical potentials difference of electrons with opposite spins is the analog of external magnetic field in the nonequilibrium case. Characteristic feature of this effective magnetic field $H^{\mathrm{eff}}(x)$ is the spatial nonuniformity which results in the finite length of HM state of the metamagnet. In the ferromagnetic metal—metamagnetic metal contact spin accumulation and therefore effective magnetic field is generated in the region on the order of spin relaxation length at the vicinity of contact with ferromagnet and at the domain wall between HM and LM states of the metamagnet. We assume that the domain wall thickness is much smaller than the spin-relaxation length. Schematically, the contact of ferromagnetic metal—metamagnetic metal with HM state is shown in Fig. 2. HM state is located at $0<x<d$. HM state emerges at electric currents such that the effective magnetic field is $H^{\mathrm{eff}}(x=0)\geq H_{\mathrm{m}}$. If d is of the order or larger than the spin-relaxation length then effective magnetic field $H^{\mathrm{eff}}(x)$ can be estimated as a sum $H^{\mathrm{eff}}(x)=H^{\mathrm{eff}}_{\mathrm{F\text{-}m}}(x)+H^{\mathrm{eff}}_{\mathrm{m\text{-}p}}(x)$ of the fields due to spin accumulation at boundary $x=0$

$$H^{\mathrm{eff}}_{\mathrm{F\text{-}m}}(x)=\frac{eJ}{g\mu_B}\frac{2R_{\mathrm{F}}R_{\mathrm{m}}}{R_{\mathrm{F}}+R_{\mathrm{m}}}[\Pi_{\mathrm{F}}-\Pi_{\mathrm{m}}]e^{-x/\ell_{\mathrm{m}}} \tag{1}$$

and effective field due to spin accumulation at domain wall $x=d$

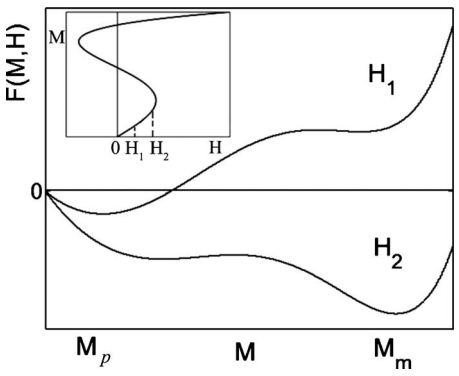

FIG. 1. Free energy $F(H,M)$ dependence on the magnetization M of the metamagnet shown schematically for different magnetic fields $H_2>H_1$. The state with high magnetization has lower energy at higher magnetic fields. Inset: dependence of the magnetization on magnetic field.

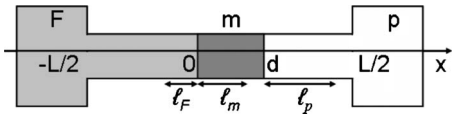

FIG. 2. Ferromagnetic metal $x \in (-L/2,0)$—metamagnetic metal $x \in (0,L/2)$ contact. (p) defines the low magnetization state of the metamagnet and (m) stands for the high magnetization state induced by the spin injection from the ferromagnet (f). ℓ_F, ℓ_m, ℓ_p are the spin diffusion lengths in ferromagnet and metamagnet in high and low magnetization states.

$$H^{\text{eff}}_{\text{m-p}}(x) = \frac{eJ}{g\mu_B}\frac{2R_mR_p}{R_m+R_p}\Pi_m e^{-(d-x)/\ell_m}. \tag{2}$$

This case is shown by the solid line in Fig. 3. In expressions (1) and (2) J is the current density, e is the electron charge, $\mu_B = |e|\hbar/2mc$ is the Bohr magneton and $g=2$ for electrons

$$\Pi_{F,m} = \frac{\sigma_{\uparrow F,m} - \sigma_{\downarrow F,m}}{\sigma_{\uparrow F,m} + \sigma_{\downarrow F,m}} \tag{3}$$

is proportional to the current polarizations, where $\sigma_\alpha = e^2 D_\alpha \nu_\alpha$ are the corresponding conductivities in the ferromagnetic, HM and LM states of the metamagnet for electrons with spin α, D_α is the diffusion coefficient, ν_α is the density of states at the Fermi level

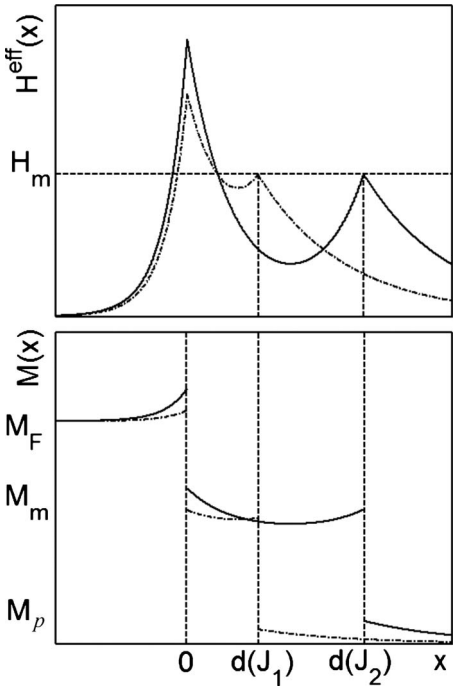

FIG. 3. Up: dependence of the effective magnetic field on coordinate for two values of the current density $|J_2| > |J_1|$. Effective magnetic field decreases in the metamagnet and the phase transition undergoes at $x=d(J)$ when $H^{\text{eff}}=H_m$. Down: magnetization profile, where M_F, M_m, M_p are the corresponding magnetizations of the ferromagnet, high and low magnetization states of the metamagnet.

$$R_{F,m} = \ell_{F,m}\frac{\sigma_{\uparrow F,m} + \sigma_{\downarrow F,m}}{4\sigma_{\uparrow F,m}\sigma_{\downarrow F,m}}, \quad R_p = \frac{\ell_p}{\sigma_p} \tag{4}$$

are the effective resistances and the spin-relaxation lengths are defined as $\ell = \sqrt{\bar{D}t_s}$, where in each state $\bar{D} = (D_\uparrow\sigma_\downarrow + D_\uparrow\sigma_\downarrow)/(\sigma_\uparrow + \sigma_\downarrow)$ and t_s is the spin-relaxation time.

In the case of small thickness of domain wall compared to the spin-relaxation length, the transition between HM and LM states of the metamagnet takes place at $x=d$ when

$$H^{\text{eff}}(d) = H_m \tag{5}$$

as shown in Fig. 3. Taking the sum of expressions (1) and (2) we estimate the corresponding length of the HM state region at $d \geq \ell_m$ as

$$d \sim \ell_m \ln\left|\frac{R_F[\Pi_F - \Pi_m]/(R_m+R_F)}{g\mu_B H_m/eJ2R_m - R_p\Pi_m/(R_m+R_p)}\right|. \tag{6}$$

At large electrical current when $g\mu_B H_m/eJ2R_m \to R_p\Pi_m/(R_m+R_p)$, according to expression (6) the length of HM state region increases $d \to \infty$. Threshold current density dependence of d occurs because of spin accumulation generation at the domain wall between HM and LM states of the metamagnet. HM state self propels into the bulk of the metamagnet and the length d might be larger than the spin relaxation length in the metamagnet ℓ_m. However, since the effective field in most part of the region is below H_m, the energy of stationary HM state at large d becomes smaller than the energy of LM state. We propose that the system must undergo to LM state at large values of the current density. More detailed discussion of the transition is given below.

In Sec. II we derive the expression for the distribution function in the ferromagnet-metamagnet (F-m) system. In Sec. III we examine the contact between ferromagnet and metamagnet in the LM state. In the linear response on applied voltage the spin-dependent part of the distribution function enters self-consistency equation for the magnetization in the system as magnetic field. Effective magnetic fields are calculated. In Sec. IV the contact between ferromagnet and metamagnet in the HM state is considered. We derive the equation for the transition between HM and LM states and self-consistently determine the length of the HM state region. We discuss different realizations of spin accumulation in metamagnet. We show that with increasing current density the system undergoes LM to HM transition while at some maximum value of the current density HM state becomes energetically unfavorable and LM state is realized in the metamagnet. The corresponding values of the current density are calculated. We discuss the HM state in ferromagnet-metamagnet-ferromagnet structure. Finally, we briefly summarize our findings in Sec. V and discuss experimental applicability.

II. ELECTRICAL SPIN INJECTION

Consider the spin-injection process from the ferromagnetic metal to metamagnetic metal. We focus on the spin and charge transports in the presence of the spin-orbit coupling and the short-range exchange electron-electron interactions.

We assume the vector of the nonequilibrium magnetization in the metamagnetic metal to be parallel to the vector of the magnetization in the ferromagnet. The Green's function in Keldysh technique in the matrix form

$$\underline{\hat{G}} = \begin{pmatrix} \hat{G}^R & \hat{G}^K \\ 0 & \hat{G}^A \end{pmatrix}$$

is given by retarded $\hat{G}^R(x,x')$, advanced $\hat{G}^A(x,x')$ and Keldysh function $\hat{G}^K(x,x')$, where $x=(\mathbf{r},t)$ denote position and time arguments, hat () stands for the matrix in spin space. Further we will consider the stationary regime in which function $\underline{\hat{G}}$ satisfies the equation

$$\left\{\left[\omega + \frac{1}{2m}\nabla_{\mathbf{r}}^2 + \mu - U(\mathbf{r}) - e\phi(\mathbf{r})\right] \times \hat{1} - \hat{U}_{so}(\mathbf{r}) + \hat{\varepsilon}(\mathbf{r})\right\}\underline{\hat{G}}(\mathbf{r},\mathbf{r}',\omega) = \hat{1}\delta(\mathbf{r}-\mathbf{r}'),$$

where $\phi(\mathbf{r})$ is the electrostatic potential, $U(\mathbf{r})$ is the random potential of impurities assumed to be Gaussian distributed with $\langle U(\mathbf{r})\rangle=0$, $\langle U(\mathbf{r})U(\mathbf{r}')\rangle=2\pi\nu\tau\delta(\mathbf{r}-\mathbf{r}')$, τ is the mean-free time and $\nu=(\nu_\uparrow+\nu_\downarrow)/2$ is the density of states. Spin-orbit interactions of electrons with impurities is described by the potential $\hat{U}_{so}(\mathbf{r})=i\beta\hat{\sigma}[\nabla U(\mathbf{r})\times\nabla]$, where β is the spin-orbit coupling constant and $\hat{\sigma}$ is the Pauli matrix. The contribution of the short-range electron-electron exchange interactions to the spin splitting[14] is described by the term $\hat{\varepsilon}(\mathbf{r})$

$$\varepsilon_\alpha(\mathbf{r}) = \frac{-i\lambda}{2}\int \frac{d\mathbf{p}d\omega}{(2\pi)^4} G^K_{-\alpha}(\mathbf{r},\mathbf{p},\omega),$$

where λ is the electron coupling constant. It is convenient to apply the Fourier transformation with respect to the relative coordinates $\mathbf{r}_1=\mathbf{r}-\mathbf{r}'$ as

$$\underline{\hat{G}}(\mathbf{R},\mathbf{p},\omega) = \int d^3\mathbf{r}_1 \underline{\hat{G}}(\mathbf{R}+\mathbf{r}_1/2,\mathbf{R}-\mathbf{r}_1/2)e^{-i\mathbf{p}\mathbf{r}_1}$$

in which $\mathbf{R}=(\mathbf{r}+\mathbf{r}')/2$. The retarded and advanced Green's functions $\hat{G}^R$ and $\hat{G}^A$ averaged over disorder in the $\mu\tau\gg1$ approximation are diagonal in spin and are given by

$$\hat{G}^{R,A}(\mathbf{R},\mathbf{p},\omega) = \frac{1}{\omega - \xi_{\mathbf{p}} + \hat{\varepsilon}(\mathbf{R}) \pm i\hat{\gamma}}, \tag{7}$$

where $\xi_{\mathbf{p}}$ is the electron dispersion, $2\gamma_\alpha=\tau_\alpha^{-1}+(t_\alpha^{-1}-t_{-\alpha}^{-1})/2$ and $\tau_\alpha^{-1}=\tau_{0\alpha}^{-1}+\tau_{s\alpha}^{-1}$ is the inverse scattering times due to disorder and spin-orbit interactions for the spin state α, $t_{s\alpha}^{-1}=4/3\tau_{s\alpha}$.[15] We assume that the momentum-relaxation time $\tau_{0\alpha}$ is smaller than the time $t_{s\alpha}$ corresponding to the spin-flip process. Let us note, that we are considering the metamagnet when the exchange energy is the coordinate-dependent function. In deriving the equation for the function $\hat{G}^K$ we assume the limit when the exchange energy is small compared to the Fermi energy $|\varepsilon_\downarrow-\varepsilon_\uparrow|/\mu<1$. In this limit the equation for the function $\hat{G}^K$ yields

$$\mathbf{v}(\nabla_{\mathbf{R}} + [\nabla_{\mathrm{R}}\varepsilon_\alpha + e\mathbf{E}]\partial_{\varepsilon_p})G^K_\alpha = -\left(\frac{1}{\tau_\alpha} - \frac{1}{t_{\alpha s}} + \frac{1}{t_{-\alpha s}}\right)G^K_\alpha + \left(\frac{F_\alpha}{\tau_\alpha} - \frac{F_\alpha - F_{-\alpha}}{2t_{\alpha s}}\right)[G^R_\alpha - G^A_\alpha]$$

here $\mathbf{E}=-\nabla\phi(\mathbf{r})$ is the electric field and we denote the coordinate and frequency-dependent function

$$F_\alpha(\mathbf{R},\omega) = \frac{i}{2\pi\nu_\alpha}\int \frac{d\mathbf{p}}{(2\pi)^3} G^K_\alpha(\mathbf{R},\mathbf{p},\omega).$$

In the diffusion approximation for the function $F_\alpha(\mathbf{R},\omega)$ one obtains the equation

$$\nabla\sigma_\alpha\nabla F_\alpha(\mathbf{R},\omega) = \frac{\nu_\alpha\nu_{-\alpha}}{2\nu}\frac{F_\alpha(\mathbf{R},\omega) - F_{-\alpha}(\mathbf{R},\omega)}{t_s}, \tag{8}$$

where $\sigma_\alpha=e^2\nu_\alpha D_\alpha$ is the conductivity, $D_\alpha=v_\alpha^2\tau_\alpha/3$ is the diffusion coefficient and the density of states nu_α are the space-dependent functions.

Let us consider the system when functions in Eq. (8) depend on one spatial coordinate (x) only. Consider the interface between a ferromagnetic metal that occupies the region ($x<0$) and a metamagnetic metal ($x>0$). We assume that the lengths of the ferromagnetic and metamagnetic regions $L/2$ are much larger than the corresponding spin-diffusion lengths. We also assume the external reservoirs of the sample at $x=\pm L/2$ to be in the spin equilibrium state. The electric field in the system is treated through the boundary conditions

$$F_\alpha(-L/2,\omega) = f(\omega - eV/2),$$

$$F_\alpha(L/2,\omega) = f(\omega + eV/2), \tag{9}$$

where $f(\omega)=\tanh(\omega/2T)$ and $V=E/L$ is the potential difference across the structure. The solution of Eq. (8) is the continuous function at the interface between ferromagnet and metamagnet and between HM and LM states of the metamagnet

$$F_\alpha(0-,\omega) = F_\alpha(0+,\omega),$$

$$F_\alpha(d-,\omega) = F_\alpha(d+,\omega) \tag{10}$$

under the assumption that the thickness of the domain wall between HM and LM states are smaller than the spin-relaxation length. The derivatives satisfy the following condition:

$$\sigma_\alpha\frac{\partial F_\alpha(x,\omega)}{\partial x}\bigg|_{x=0-} = \sigma_\alpha\frac{\partial F_\alpha(x,\omega)}{\partial x}\bigg|_{x=0+},$$

$$\sigma_\alpha\frac{\partial F_\alpha(x,\omega)}{\partial x}\bigg|_{x=d-} = \sigma_\alpha\frac{\partial F_\alpha(x,\omega)}{\partial x}\bigg|_{x=d+} \tag{11}$$

describing the continuity of the current density at the interface. The current density carried by spin-up and spin-down electrons is given as

$$J_\alpha(x) = \frac{1}{2e}\int \sigma_\alpha \frac{\partial F_\alpha(x,\omega)}{\partial x} d\omega.$$

We solve Eq. (8) for the case of the ferromagnet—LM state of the metamagnet contact and for the case of the ferromagnet-HM-LM contact. The solution of Eq. (8) can be considered independently in the vicinity of the boundary between the ferromagnet and HM state of the metamagnet, and at the domain wall between LM and HM states in the limit when the length of the HM state $d > \ell_{\rm m}$. Taking into account the length of the system to be larger than the corresponding spin-diffusion lengths we solve the diffusion equation in the region $x>0$ with boundary in Eq. (9) and continuity in Eqs. (10) and (11) conditions in the vicinity to the boundary with the ferromagnet

$$F_{\uparrow,\downarrow|{\rm p,m}}(x,\omega) = f(\omega + eV/2) + A_{\rm p,m}\Big[(x - L/2) \pm 2\sigma_{\downarrow,\uparrow|{\rm p,m}} \times (\Pi_{\rm F} - \Pi_{\rm p,m})\frac{R_{\rm F}R_{\rm p,m}}{(R_{\rm F}+R_{\rm p,m})} e^{-x/\ell_{\rm p,m}}\Big], \quad (12)$$

where p,m denotes LM and HM states of the metamagnet and F stands for the ferromagnet, coefficient

$$A_{\rm p,m} = \frac{2(\sigma_{\uparrow{\rm F}} + \sigma_{\downarrow{\rm F}})[f(\omega + eV/2) - f(\omega - eV/2)]}{[(\sigma_{\uparrow{\rm F}} + \sigma_{\downarrow{\rm F}}) + (\sigma_{\uparrow|{\rm p,m}} + \sigma_{\downarrow|{\rm p,m}})]L}$$

is connected with the current density as

$$J = J_\uparrow(x) + J_\downarrow(x) = \frac{1}{2e}\int [\sigma_{\uparrow|{\rm p,m}} + \sigma_{\downarrow|{\rm p,m}}]A_{\rm p,m} d\omega.$$

The values $\Pi_{\rm F,m}$ are proportional to the current polarization and resistivities $R_{\rm F,m,p}$ in the ferromagnet and metamagnet are defined by expressions (3) and (4). Note, that in the LM state of the metamagnet conductivities $\sigma_{\uparrow{\rm p}} = \sigma_{\downarrow{\rm p}} = \sigma_{\rm p}/2$ and diffusion coefficients $D_{\uparrow{\rm p}} = D_{\downarrow{\rm p}} = D_{\rm p}$. Solution (12) has to be supplemented by the local neutrality condition which self-consistently determines the electric potential in the sample. The spin-injection process does not change concentration of electrons

$$N = \frac{1}{2}\int [\nu_\uparrow F_\uparrow(x,\omega) + \nu_\downarrow F_\downarrow(x,\omega)] d\omega. \quad (13)$$

III. LOW MAGNETIZATION STATE

The self-consistency equation for the magnetization density $M(x)$ in the sample is defined as

$$M(x) = g\mu_B[\varepsilon_\downarrow(x) - \varepsilon_\uparrow(x)]/\lambda = -\frac{g\mu_B}{2}\int [\nu_\uparrow F_\uparrow(x,\omega) - \nu_\downarrow F_\downarrow(x,\omega)] d\omega. \quad (14)$$

In the case of equilibrium metamagnetic metal, Eq. (14) has two solutions even without the external magnetic field, corresponding to two minima of free energy, see inset in Fig. 1. Transition between these solutions takes place when magnetic field is equal to $H_{\rm m}$. One could verify that in the linear on V response the spin-dependent part of expression (12) enters expressions (13) and (14) as magnetic field.

First, consider the case of the contact at $x=0$ between the ferromagnet and LM sate of the metamagnet which is similar to the case of spin injection to paramagnetic metal. In the linear response, using Eqs. (12) and (14), the effective field in the LM state due to spin accumulation is

$$H_{\rm p}^{\rm eff}(x) = \frac{eJ}{g\mu_B}\frac{2R_{\rm F}R_{\rm p}}{R_{\rm F}+R_{\rm p}}\Pi_{\rm F} e^{-x/\ell_{\rm p}}$$

and magnetization at $x>0$ is

$$M_{\rm p}(x) = \frac{(g\mu_B)^2\nu_{\rm p}}{1-\lambda\nu_{\rm p}} H_{\rm p}^{\rm eff}(x). \quad (15)$$

Effective magnetic field in the LM state as well as the magnetization is proportional to the current density and decreases into the bulk of the metamagnet on the spin-relaxation length.

Effective magnetic field produced by the spin accumulation in the ferromagnetic metal at $x<0$ is

$$H_{\rm p\text{-}F}^{\rm eff}(x) = \frac{eJ}{g\mu_B}\frac{2R_{\rm F}R_{\rm p}}{R_{\rm F}+R_{\rm p}}\Pi_{\rm F} e^{x/\ell_{\rm F}} \quad (16)$$

here expressions for resistances $R_{\rm F}$ and $R_{\rm p}$ are given by Eq. (4).

IV. METAMAGNETIC TRANSITION

Now let us consider the contact between the ferromagnet and the metamagnet being in the HM state. The procedure of finding solutions is following. We assume that there is HM state of the metamagnet in the system at $0<x<d$. Then we solve Eq. (8) for the spin accumulation at two boundaries at $x=0$, $x=d$, and self consistently determine the value of d from Eq. (5).

To obtain Eq. (5) we need to consider the metamagnetic transition in more detail. Near the transition between HM and LM states we need to include the spatial derivatives of magnetization into consideration so

$$-K\frac{d^2}{dx^2}M + \frac{\delta F[H_{\rm m}^{\rm eff}(x), M]}{\delta M} = 0$$

here K is positive constant. Let us have solution $M_w(x-d)$, describing the transition between HM and LM states at point $x=d$ in uniform magnetic field. It is the solution of equation

$$-K\frac{d^2}{dx^2}M_w + \frac{\delta F(H_{\rm m}, M_w)}{\delta M_w} = 0.$$

Assuming small difference $H_{\rm m}^{\rm eff}(x) - H_{\rm m}$ at $x \approx d$ and substituting $M = M_w(x-d) + \delta M$, we obtain

$$-K\frac{d^2}{dx^2}\delta M + \frac{1}{2}\frac{\delta^2 F(H_{\rm m}, M)}{\delta M^2}\Big|_{M=M_w} \delta M = H_{\rm m}^{\rm eff}(x) - H_{\rm m}.$$

Solution of this equation exists if

$$\int dx\Psi_0(x)[H_{\rm m}^{\rm eff}(x)-H_{\rm m}]=0, \tag{17}$$

where $\Psi_0(x)$ is the eigenfunction, corresponding to zero $E_0=0$ mode of equation

$$-K\frac{d^2}{dx^2}\Psi_k+\frac{1}{2}\frac{\delta^2 F(H_{\rm m},M)}{\delta M^2}\bigg|_{M=M_w}\Psi_k=E_k\Psi_k$$

$\Psi_0(x)$ has no zeros and is localized near $x=d$ in region on the order of domain wall thickness. This mode describes small translation of M so in the uniform field one has $E_0=0$. In the case when $\ell_{\rm m,p}$ are much larger than the domain wall thickness from condition (17) one obtains Eq. (5).

A. High magnetization state

In HM state region the magnetization is

$$M_{\rm m}(x)=M_{\rm m}^0+\frac{(g\mu_B)^2\nu_{\rm m}}{1-\lambda\nu_{\rm m}}H_{\rm m}^{\rm eff}(x).$$

Here $\nu_{\rm m}=2\nu_{\uparrow{\rm m}}\nu_{\downarrow{\rm m}}/(\nu_{\uparrow{\rm m}}+\nu_{\downarrow{\rm m}})$, $M_{\rm m}^0$ is the magnetization of HM state of the metamagnet, calculated at zero effective magnetic field, $H_{\rm m}^{\rm eff}$ is the effective magnetic field in the HM state given as a sum of effective fields in Eqs. (1) and (2) due to spin injection at boundary $x=0$ and domain wall $x=d$. Let us discuss different realizations of spin accumulation. (1) Consider the case when $\Pi_{\rm F}-\Pi_{\rm m}$ and $\Pi_{\rm m}$ given by expression (3) have the same sign. Effective fields in Eqs. (1) and (2) of contacts at $x=0$ and $x=d$ have same sign too. The estimation for the length of HM state region d in the limit $d\geq\ell_{\rm m}$ is given by expression (6). d diverges at some threshold value of electrical current density. (2) Let $\Pi_{\rm F}-\Pi_{\rm m}$ and $\Pi_{\rm m}$ have opposite signs. Thus, effective fields of both contacts have different signs too. Analysis shows that solution of Eq. (5) with finite d exist at $|H_{\rm F\text{-}m}^{\rm eff}(0)|>|H_{\rm m\text{-}p}^{\rm eff}(d)|$. In this case d stays finite with the increase in the electrical current density.

Spin accumulation appears also in the ferromagnetic metal at $x<0$ as

$$H_{\rm m\text{-}F}^{\rm eff}(x)=\frac{eJ}{g\mu_B}\frac{2R_{\rm F}R_{\rm m}}{R_{\rm F}+R_{\rm m}}[\Pi_{\rm F}-\Pi_{\rm m}]e^{x/\ell_{\rm F}} \tag{18}$$

here expressions for $R_{\rm F}$ and $R_{\rm m}$ are given by Eq. (4).

B. Free energy criterion

We propose that the realization of HM state must be energetically favorable over the realization of the paramagnetic state. In the linear on the applied current regime the magnetic part of the free energy in the case of LM state realization is

$$\delta\mathcal{F}_{\rm Fp}=-M_{\rm F}\int_{-L/2}^{0}H_{\rm p\text{-}F}^{\rm eff}(x)dx,$$

where $M_{\rm F}$ is the magnetization of ferromagnetic contact and $H_{\rm p\text{-}F}^{\rm eff}(x)$ is given by expression (16). In the case of HM state realization it is

$$\delta\mathcal{F}_{\rm Fmp}=-M_{\rm F}\int_{-L/2}^{0}H_{\rm m\text{-}F}^{\rm eff}(x)dx-M_{\rm m}^0\int_0^d[H_{\rm m}^{\rm eff}(x)-H_{\rm m}]dx+F_S.$$

Effective magnetic fields in ferromagnetic region are given by expressions (16) for the case of the ferromagnet-LM state realization and by Eq. (18) for the case of ferromagnet-HM-LM regime. F_S is the energy, associated with domain wall and boundary between ferromagnet and HM state (F-m). While the domain wall energy is positive, the sign of F-m boundary energy depends on relative directions of magnetizations in the ferromagnet and metamagnet. Estimation of F_S depends on details that are beyond the scope of the paper.

From criterion $\delta\mathcal{F}_{\rm Fp}-\delta\mathcal{F}_{\rm Fmp}\geq 0$ for the realization of metamagnetic transition one can estimate the maximum value of the current density. To make the expression more transparent one suggests the case $R_{\rm F}>R_{\rm m}>R_{\rm p}$, which assumes the contribution of the boundary m-p and F-p to the free energy is smaller than the corresponding contribution from the F-m interface, one can estimate as

$$J_{max}\approx\frac{g\mu_B}{e}\frac{H_{\rm m}/2R_{\rm m}}{[\Pi_{\rm F}-\Pi_{\rm m}](1+\ell_{\rm F}M_{\rm F}/\ell_{\rm m}M_{\rm m}^0)}\frac{d(J_{max})}{\ell_{\rm m}},$$

where the length of the HM state of the metamagnet $d(J_{max})$ is given by expression (6). To summarize, the HM state is realized at current densities such that $J_0<J<J_{max}$. The value of current density J_0 can be estimated from expression (1), where $H_{\rm F\text{-}m}^{\rm eff}(0)=H_{\rm m}$, as

$$J_0\approx\frac{g\mu_B}{e}\frac{H_{\rm m}/2R_{\rm m}}{[\Pi_{\rm F}-\Pi_{\rm m}]}.$$

If the current density is increased further $J>J_{max}$ then the LM state is realized in the metamagnet.

C. Ferromagnet-metamagnet-ferromagnet structure

Let us briefly discuss the spin injected HM state in the system with metamagnetic metal of length Δ placed between two ferromagnetic metals having opposite directions of magnetizations. In this case $\delta\mathcal{F}_{\rm Fp}=0$, because of the cancellation of contributions in ferromagnets with opposite magnetizations. In the HM state of the metamagnet

$$\delta\mathcal{F}_{\rm FmF}=-M_{\rm m}^0\int_0^{\Delta}[H_{\rm m}^{\rm eff}(x)-H_{\rm m}]dx.$$

Both ferromagnets contribute equally to the effective field. At $\Delta\geq\ell_{\rm m}$ using expression (1) we obtain the maximum value of electrical current density at which $\delta\mathcal{F}_{\rm FmF}\leq 0$ as

$$J_{max}=\frac{g\mu_B}{e}H_{\rm m}\frac{R_{\rm F}+R_{\rm m}}{4R_{\rm F}R_{\rm m}[\Pi_{\rm F}-\Pi_{\rm m}]}\frac{\Delta}{\ell_{\rm m}}.$$

Note, that the expression for J_{max} for the F-m contact in the limit discussed in the previous section is similar to the F-m-F

contact. Also note, that the transition to LM state of the metamagnet with increasing current is absent.

V. CONCLUSIONS

The system for experimental study of spin-injected metamagnetic transition must have low metamagnetic field, large spin relaxation length, and sustain high electrical current density. Typical values of the spin accumulation in paramagnetic metals are in the microelectron volt range,[16,17] which corresponds to the effective magnetic fields in tenth millitesla range at reasonably high current density. On the other hand, in the magnetic multilayered systems, in which current is injected through the point contact, the estimated values of effective magnetic fields might be on the order of Tesla.[18]

Metallic metamagnets with metamagnetic field in Tesla's range are well known,[19] however applying external magnetic field one can easily bring such system close to the transition. Well studied YCo_2 in crystal form undergoes the metamagnetic transition at magnetic field,[13] which is much higher than effective fields achievable in the spin injection mechanism, while it is a weak ferromagnet in the nanoscale structured form,[20] suggesting the possibility of metamagnetic field reducing at proper technology.

Other possibility is to study the system with temperature-induced metamagnetic transition[21] or near first-order ferromagnetic transition.[22] Typical value of spin-relaxation length in *d*-electron ferromagnets is on the order of tenth nanometer. Unfortunately, spin relaxation length, the main parameter that governs the magnitude as well as the spatial distribution of effective field, was not studied in metamagnetic systems.

To conclude, we have studied the metamagnetic transition of itinerant electrons in the metamagnetic metal under the spin injection from the ferromagnetic metal. Spin injection produces the nonequilibrium effective magnetic field in metamagnet which drives the transition. We have calculated the effective magnetic fields and electrical currents required for the metamagnetic transition. We have shown that the length of HM state of the metamagnet has threshold dependence on electrical current due to the effective magnetic field self generated at domain wall between HM and LM states.

ACKNOWLEDGMENTS

We thank V. I. Kozub and A. T. Burkov for valuable discussion. We are grateful for the financial support of Grant of Saint-Petersburg under Grant No. 29.0109.077 and RFFI under Grant No. 09-02-01285-A.

[1] A. G. Aronov, JETP Lett. **24**, 32 (1976).
[2] M. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985).
[3] P. C. van Son, H. van Kempen, and P. Wyder, Phys. Rev. Lett. **58**, 2271 (1987).
[4] M. Johnson and R. H. Silsbee, Phys. Rev. B **37**, 5312 (1988).
[5] T. Valet and A. Fert, Phys. Rev. B **48**, 7099 (1993).
[6] S. Hershfield and H. L. Zhao, Phys. Rev. B **56**, 3296 (1997).
[7] E. I. Rashba, Eur. Phys. J. B **29**, 513 (2002); Semicond. Sci. Technol. **23**, 114015 (2008).
[8] I. Žutić, J. Fabian, and S. Das Sarma, Rev. Mod. Phys. **76**, 323 (2004).
[9] *Spin Physics in Semiconductors*, edited by M. I. Dyakonov (Springer, New York, 2008).
[10] F. J. Jedema, M. V. Costache, H. B. Heersche, J. J. A. Baselmans, and B. J. van Wees, Appl. Phys. Lett. **81**, 5162 (2002).
[11] F. J. Jedema, M. S. Nijboer, A. T. Filip, and B. J. van Wees, Phys. Rev. B **67**, 085319 (2003).
[12] E. P. Wohlfarth and P. Rhodes, Philos. Mag. **7**, 1817 (1962).
[13] T. Goto, K. Fukamichi, T. Sakakibara, and H. Komatsu, Solid State Commun. **72**, 945 (1989).
[14] R. White, *Quantum Theory of Magnetism* (Springer-Verlag, Berlin, 1983).
[15] B. L. Altshuler and A. G. Aronov, in *Electron-Electron Interactions in the Disordered Conductors*, edited by A. L. Efros and M. Pollak (Elsevier, New York, 1985).
[16] A. Fert, J.-M. George, H. Jaffres, and G. Faini, J. Phys. D **35**, 2443 (2002).
[17] M. Zaffalon and B. J. van Wees, Phys. Rev. Lett. **91**, 186601 (2003).
[18] M. Tsoi, A. G. M. Jansen, J. Bass, W.-C. Chiang, M. Seck, V. Tsoi, and P. Wyder, Phys. Rev. Lett. **80**, 4281 (1998).
[19] T. Goto, H. A. Katori, T. Sakakibara, H. Mitamura, K. Fukamichi, and K. Murata, J. Appl. Phys. **76**, 6682 (1994).
[20] S. N. Jammalamadaka, E. V. Sampathkumaran, V. S. N. Murthy, and G. Markandeyulu, Appl. Phys. Lett. **92**, 192506 (2008).
[21] A. S. Markosyan and V. E. Rodimin, J. Magn. Magn. Mater. **300**, e518 (2006).
[22] H. Yamada and T. Goto, Phys. Rev. B **68**, 184417 (2003).