

TUNNELING INDUCED MAGNETIZATION IN THE NORMAL METAL/FERROMAGNET SANDWICH

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Tunneling magnetization mechanisms in the N/F sandwich where N is a normal metal and F is a ferromagnet are considered. Nonlinear equations describing the magnetic properties of N and F are obtained using the Keldysh—Green function approach. The equations include self-consistency equations for the intrinsic molecular fields \mathbf{h}_N and \mathbf{h}_F completed by the kinetic equation for the spin imbalance distribution function $f_{2,\varepsilon}$. We examine: (i) the proximity magnetization caused by a direct tunneling interaction and (ii) the nonequilibrium spin imbalance magnetization. The set of nonlinear equations has multiple solutions, which are interpreted as magnetization domains induced by the spin-polarized tunneling when the bias voltage V across the N/F sandwich is applied.

The recent progress in growing ferromagnetic tunnel junctions with reproducible characteristics [1–3] stimulated widespread interest in various hybrid N/F- and F/N/F-devices [4–7] (F is a ferromagnet, N is a normal metal or a ferromagnet with a smaller magnetization as compared to F). The tunnel junctions are formed by N and F thin spacers (see, e.g., Fig. 1, *a*) separated by interface dielectric barrier I . Among most remarkable properties of the ferromagnetic junctions one may quote the tunneling induced magnetization [4–5], magnetoresistance [8, 9], and interlayer exchange coupling [10–13]. According to [5, 14], when a bias voltage V is applied across the hybrid device, the N electrode is magnetized due to the spin-polarized electron tunneling [7] which increases the spin density in N or changes it in F (i.e., $N_\uparrow \neq N_\downarrow$, where $N_{\uparrow(\downarrow)}$ is the concentration of electrons with spin “ \uparrow ” (“ \downarrow ”) in N). Inside the N lead, the spin accumulates [15] on the spin flip length $\xi_{sf} \simeq \tau_{sf} v_F$ (τ_{sf} being the spin flip time, v_F being the Fermi velocity), when the tunneling rates $\Gamma_N^{\uparrow\uparrow}$ and $\Gamma_N^{\downarrow\downarrow}$ from F to N for the electrons with spins “ \uparrow ” and “ \downarrow ” are different. The spin accumulation $N_\uparrow - N_\downarrow \neq 0$ in N causes a finite magnetization $M_N = \mu_B (N_\uparrow - N_\downarrow)$. The last formula may also be rewritten as $M_N \simeq \varpi_1 V$ [where $\varpi_1 \propto \tau_{sf} (\Gamma_N^{\uparrow\uparrow} - \Gamma_N^{\downarrow\downarrow})$] that emphasizes a nonequilibrium origin of the induced magnetization.

In this paper, we consider a magnetization instability induced inside the N lead by the nonequilibrium spin injection from an adjacent F lead. The multiple values of $\mathbf{h}_N^{(i)}$ (i is the domain index) raised at a fixed V in such a nonlinear system are interpreted as magnetization domains whose total number is N_{dom} .

The nonequilibrium magnetization mechanism of the N/F sandwich is studied using the Keldysh—Green function technique [16]. In this paper, we implement the methods [16, 17] in respect to magnetic tunneling junctions. We derive a closed set of equations from simple basic principles. The set includes the self-consistency equations for molecular fields completed by quantum kinetic equations. The equations are used then to study metastable states characterized by different magnetizations. Also we discuss how the predicted effects may be observed experimentally.

We analyze two distinct mechanisms of the tunneling-mediated interaction [17] that may considerably affect the magnetic properties of the N/F sandwich in the interface vicinity. One mechanism originates from overlapping the electron wavefunctions of N and F. When an electron, e.g., with a spin “ \uparrow ” tunnels from F to N, its former wavefunction $|\alpha_F\rangle$ is modified to a new state $|\alpha_N\rangle$ in N. The quantum mechanical transition time τ_N between $|\alpha_F\rangle$ and $|\alpha_N\rangle$ is finite and is estimated as $\tau_N \simeq \hbar/h_F$ where $h_F = \mu_B H_F$ being the Zeeman splitting energy. It is supposed that a spin-polarized electron travels a finite distance $\xi_N = v_F \tau_N = \hbar v_F / h_F$ inside the N lead after its penetration from F (see, i.e., Fig. 1, *a*). For that reason, a thin slab of the N spacer near the N/F interface is magnetized on the length $\sim \xi_N \ll \xi_{sf}$ due to its proximity to the ferromagnet F. For ferromagnets used in known experiments [1, 2], typical values are $h_F \simeq 50 \div 500$ mV that correspond to $\xi_N \simeq 2 \div 20$ nm. As we will see later, the aforementioned proximity magnetization depends on the bias voltage V in a nonlinear way. Another mechanism acts only when a

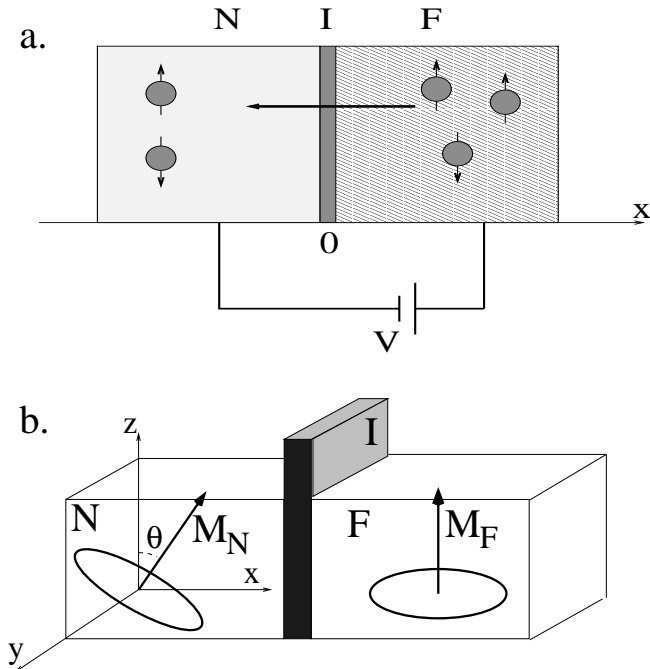


Fig. 1. *a* – the N/F sandwich where conducting electrons in the F electrode are spin-polarized by the intrinsic molecular magnetic field \mathbf{h}_F . *b* – the vector \mathbf{M}_N of magnetization induced in N by the nonequilibrium spin injection. Under nonequilibrium conditions, \mathbf{M}_N is tilted by angle θ in respect to the primary magnetization \mathbf{M}_F in F

finite bias voltage V is applied across the N/F sandwich, spreading to a much longer distance $\sim \xi_{sf}$. It arises when the tunneling current of spin-polarized electrons magnetizes the N spacer at the expense of the spin accumulation when the tunneling rates $\Gamma_N^{\uparrow\uparrow}$ and $\Gamma_N^{\downarrow\downarrow}$ of electrons with opposite spins “ \uparrow ” and “ \downarrow ” differ. At a given energy ε , the above process is described by the nonequilibrium spin distribution function $f_{2,\varepsilon} = (f_{\uparrow\varepsilon} - f_{\downarrow\varepsilon})/2$ which serves as a measure of the spin imbalance in N. If $\Gamma_N^{\uparrow\uparrow} \neq \Gamma_N^{\downarrow\downarrow}$, the spin distribution may essentially deviate from equilibrium (where $f_{2,\varepsilon} = 0$) in the energy interval $\sim \max\{h_{F(N)}, T, \hbar/\tau_{sf}\}$. Because such energy interval is limited, it means that the whole nonequilibrium scenario depends on properties of the leads, i.e., on the parameters $h_{F(N)}$, T , and τ_{sf} . The spin imbalance ($f_{2,\varepsilon} \neq 0$) persists in the N/F interface vicinity on the distance of spin flip length $\sim \xi_{sf}$.

Let us consider the N/F-sandwich (see, e.g., Fig. 1, *a*) formed by two thin spacers where N stands for a normal metal while F is a ferromagnet. The exchange interaction Hamiltonian

$$\hat{\mathcal{H}}_{ex} = -JS_1S_2 \quad (1)$$

(J is the exchange integral, and $\mathbf{S}_{1(2)}$ is the electron spin) originates from the spin-dependent part of the electron-electron Coulomb interaction. Then, in the mean field approximation, the part of the Hamiltonian corresponding to the Zeeman splitting energy of conduction electrons in F is written in the matrix notation as

$$\hat{\mathcal{H}}_Z = (\mathbf{S}_1, \mathbf{h}_F^{(0)}) = \sum_p \hat{c}_p^+ (\hat{\sigma}, \mathbf{h}_F^{(0)}) \hat{c}_p, \quad (2)$$

where $\hat{\sigma} = \sigma_x \mathbf{i} + \sigma_y \mathbf{j} + \sigma_z \mathbf{k}$ is the conventional Pauli spin operator, σ_i are the Pauli matrices,

$$\hat{c}_p^+ = (c_{p\uparrow}^+ \quad c_{p\downarrow}^+),$$

$$\hat{c}_p = \begin{pmatrix} c_{p\uparrow} \\ c_{p\downarrow} \end{pmatrix}$$

are two-component spinor operators, and $c_{p\uparrow}^+$ ($c_{p\uparrow}$) is the electron creation (annihilation) operator with spin “ \uparrow ”. The primary intrinsic molecular field $\mathbf{h}_F^{(0)}$ in Eq. (2) is introduced using Eq. (2) as

$$\mathbf{h}_F^{(0)} = -J \langle \mathbf{S}_2 \rangle + \mathbf{h}^d + \mathbf{h}^{ext} \quad (3)$$

where the last two terms stand for the magnetic dipole interaction and the external magnetic field, respectively. For the sake of simplicity, we disregard here the spin-orbit interaction and the Lorentz force due to the internal magnetization. The unperturbed electron Hamiltonian is

$$\hat{\mathcal{H}}_{F(N)} = \sum_p \hat{c}_p^+ \left(\varepsilon_p^{F(N)} \hat{1} + (\hat{\sigma}, \mathbf{h}_{F(N)}) \right) \hat{c}_p, \quad (4)$$

where $\varepsilon_p^{F(N)} = p^2/2m - \mu_{F(N)}$ is the electron kinetic energy in F(N), p is the electron momentum, m is the electron mass, $\mu_{F(N)}$ is the electrochemical potential in F(N), $\hat{1}$ is the 2×2 unit matrix. In Eq. (4), the matrix multiplication means the summing over the electron spin directions, while the spinor transformation at a rotation of the quantization axis within the zy -plane by an angle θ is described as $\hat{c}_p^+ \rightarrow \hat{c}_p^+ \hat{U}(\theta)$, where $\hat{U}(\theta)$ is the unitary operator

$$\hat{U}(\theta) = \begin{pmatrix} \cos \frac{\theta}{2} & \sin \frac{\theta}{2} \\ -\sin \frac{\theta}{2} & \cos \frac{\theta}{2} \end{pmatrix}. \quad (5)$$

For the sake of simplicity, we assume that the properties of N(F) and the intrinsic molecular fields $h_{N(F)}$ in a small nanoscopic junction are homogeneous on the scale of the electrode thickness $d_{N(F)} \leq \xi_{N(F)} \simeq \hbar v_{N(F)}/h_{N(F)}$ and

that the electron transport between N and F is described by the tunneling interaction

$$\hat{\mathcal{H}}_T = \sum_{p\sigma} \left[\hat{c}_{p'}^+ \hat{T}_{pp'} \hat{U}(\theta) \hat{b}_p + \text{c.c.} \right], \quad (6)$$

where $\hat{T}_{pp'}$ is the 2×2 spin-dependent tunneling matrix element

$$\hat{T}_{pp'} = \begin{pmatrix} T_{\uparrow\uparrow} & T_{\uparrow\downarrow} \\ T_{\downarrow\uparrow} & T_{\downarrow\downarrow} \end{pmatrix}_{pp'}.$$

The dependence of $\hat{\mathcal{H}}_T$ on θ means that the rotation of the quantization axis modifies the tunneling process. If one sets $T_{\uparrow\downarrow} = T_{\downarrow\uparrow} \approx 0$, then

$$\hat{T}_{pp'} \hat{U} = \hat{U}_T \approx \begin{pmatrix} T_{\uparrow\uparrow} \cos \frac{\theta}{2} & T_{\uparrow\uparrow} \sin \frac{\theta}{2} \\ -T_{\downarrow\downarrow} \sin \frac{\theta}{2} & T_{\downarrow\downarrow} \cos \frac{\theta}{2} \end{pmatrix}. \quad (7)$$

A simplified description of the nonequilibrium magnetization of the N/F sandwich is based on the assumption that other parts of the whole subsystem (e.g., phonons, magnons, spin fluctuations, electron charges, etc.) remain in equilibrium. Then the relevant effective Hamiltonian is composed by pieces (4) and (6) as

$$\hat{\mathcal{H}}_{\text{eff}} = \hat{\mathcal{H}}_F + \hat{\mathcal{H}}_N + \hat{\mathcal{H}}_T + \hat{\mathcal{H}}_{s-o}, \quad (8)$$

where $\hat{\mathcal{H}}_{s-o}$ is related to the weak spin-orbital interaction being responsible for spin-flip processes in the system. The Keldysh–Green function technique [16] implemented to the relevant part of Hamiltonian (8) allows the calculation of major characteristics of a nanoscopic N/F-sandwich in a relatively simple fashion. For instance, from the tunneling Hamiltonian (6), one can derive formulas for the tunneling electric and spin currents, while the magnetization is expressed as

$$\mathbf{M} = \frac{\mu_B}{2\pi i} \int d\varepsilon \text{Tr} \sigma \hat{f}_\varepsilon \sum_p \hat{A}_{p,\varepsilon}, \quad (9)$$

where Tr means the trace operation, $\hat{A}_{p,\varepsilon} = \text{Im} [\hat{\sigma}_3 \hat{G}_{p,\varepsilon}^{\text{R(A)}}] / \pi$ is the electron spectral density. The tunneling electron density of states is determined as $D(\varepsilon) = \text{Tr} \sum_p \text{Im} [\hat{\sigma}_3 \hat{G}_{p,\varepsilon}^{\text{R(A)}}]$. In the normal spacer, $\mathbf{M}_N \propto \langle \mathbf{S} \rangle$, where \mathbf{S} is the residual uncompensated spin of electrons tunneled from F to N, and $\langle \dots \rangle$ denotes quantum mechanical and statistical averaging. The energy-dependent electron distribution function is introduced as

$$\hat{f}_\varepsilon = \begin{pmatrix} f_{\uparrow\varepsilon} & 0 \\ 0 & f_{\downarrow\varepsilon} \end{pmatrix} = f_{1,\varepsilon} \hat{1} + f_{2,\varepsilon} \hat{\sigma}_3, \quad (10)$$

where $f_{1,\varepsilon} = (f_{\uparrow\varepsilon} + f_{\downarrow\varepsilon})/2$; $f_{2,\varepsilon} = (f_{\uparrow\varepsilon} - f_{\downarrow\varepsilon})/2$. In equilibrium $f_{\uparrow\varepsilon} = f_{\downarrow\varepsilon} = f_\varepsilon^{(0)}$ where the Fermi function $f_\varepsilon^{(0)} = 1/(\exp(\varepsilon/T) + 1)$. The rotation of the principal quantization direction is taken into account by introducing finite off-diagonal parts of the electron spectral density $A_{\uparrow\downarrow} = A_{\downarrow\uparrow} \neq 0$. The mentioned off-diagonal functions $A_{\sigma\sigma'}$ are calculated using the self-consistency equation derived below. Inside the N spacer, a finite magnetization \mathbf{M} is induced by the spin injection and is entirely determined by the nonequilibrium spin distribution function $f_{2,\varepsilon}$ found from the quantum kinetic equation derived below. The spectral density $\hat{A}_{p\varepsilon}$ is expressed through the retarded Green $\hat{G}^{\text{R(A)}}$ function

$$\left[\hat{G}^{\text{R(A)}} \right]_{p,\varepsilon}^{-1} = \left[\hat{G}_0^{\text{R(A)}} \right]_{p,\varepsilon}^{-1} + \hat{\Sigma}^{\text{R(A)}}(\varepsilon), \quad (11)$$

where in F

$$\left[\hat{G}_{\text{OF}}^{\text{R(A)}} \right]_{p,\varepsilon}^{-1} = (\varepsilon + h_F) \hat{\sigma}_3 - \varsigma_p \hat{1} \quad (12)$$

while in N

$$\left[\hat{G}_{\text{ON}}^{\text{R(A)}} \right]_{p,\varepsilon}^{-1} = (\varepsilon + h_N \cos \theta_N) \hat{\sigma}_3 - \varsigma_p \hat{1} - h_N \sin \theta_N i \hat{\sigma}_2. \quad (13)$$

In Eq. (13), we assumed that the quantization axis in N may be tilted by some angle θ_N in respect to the primary quantization axis in F. The actual magnitude of θ_N is found from the self-consistency equations for intrinsic molecular fields \mathbf{h}_F and \mathbf{h}_N derived hereafter. The poles of the retarded Green function $\hat{G}_{\text{F(N)}}^{\text{R(A)}}$ are related to the electron excitation spectrum in F(N). Also knowing the full $\hat{G}_{\text{F(N)}}^{\text{R(A)}}$, one may compute the electron spectral density $\hat{A}_{p,\varepsilon}$ or the electron density of states $D(\varepsilon)$. In Eq. (11), the self-energy is

$$\hat{\Sigma}^{\text{R(A)}}(\mathbf{p}, \varepsilon) = \hat{\Sigma}_{\text{imp}}^{\text{R(A)}}(\mathbf{p}, \varepsilon) + \hat{\Sigma}_{\text{sf}}^{\text{R(A)}}(\mathbf{p}, \varepsilon) + \hat{\Sigma}_{\text{T}}^{\text{R(A)}}(\mathbf{p}, \varepsilon) \quad (14)$$

where $\hat{\Sigma}_{\text{imp}}^{\text{R(A)}}(\mathbf{p}, \varepsilon) = \pm i/2\tau_i$, and the spin-flip self-energy $\hat{\Sigma}_{\text{sf}}^{\text{R(A)}}(\mathbf{p}, \varepsilon)$ is determined by a weak spin-orbital interaction, while the tunneling part is

$$\hat{\Sigma}_{\text{TF}}^{\text{R(A)}}(\varepsilon) = \sum_{p'} \hat{U}_T \hat{G}_N^{\text{R(A)}}(\mathbf{p}', \varepsilon) \hat{U}_T^+ = \pi i \frac{\hat{\Gamma}_a^{\text{F}} \varepsilon + \hat{\Gamma}_b^{\text{F}} \Xi_N}{\varsigma_\varepsilon^{\text{N}}} \hat{\sigma}_3, \quad (15)$$

where $\varsigma_\varepsilon^{\text{N}} = \sqrt{\varepsilon^2 + \Xi_N^2}$, $\Xi_N = \varepsilon h_N \sin \theta / [\varepsilon + h_N \cos \theta]$ is the molecular field parameter, and the tunneling rates are

$$\hat{\Gamma}_a = \begin{pmatrix} \Gamma_{\uparrow\uparrow} & 0 \\ 0 & \Gamma_{\downarrow\downarrow} \end{pmatrix} = \Gamma_1 \hat{1} + \Gamma_2 \hat{\sigma}_3,$$

$$\begin{aligned}\hat{\Gamma}_b &= \begin{pmatrix} \Gamma_{\uparrow\uparrow} & 0 \\ 0 & -\Gamma_{\downarrow\downarrow} \end{pmatrix} \sin\theta + \begin{pmatrix} 0 & \Gamma_{\uparrow\downarrow} \\ \Gamma_{\uparrow\downarrow}^* & 0 \end{pmatrix} \cos\theta = \\ &= (\Gamma_1\hat{\sigma}_3 + \Gamma_2\hat{1}) \sin\theta + (\Gamma_3\hat{\sigma}_1 + \Gamma_4i\hat{\sigma}_2) \cos\theta, \\ \Gamma_1 &= (\Gamma_{\uparrow\uparrow} + \Gamma_{\downarrow\downarrow})/2; \Gamma_2 = (\Gamma_{\uparrow\uparrow} - \Gamma_{\downarrow\downarrow})/2, \\ \Gamma_3 &= (\Gamma_{\uparrow\downarrow} + \Gamma_{\uparrow\downarrow}^*)/2; \Gamma_4 = (\Gamma_{\uparrow\downarrow} - \Gamma_{\uparrow\downarrow}^*)/2,\end{aligned}$$

where $\Gamma_{\sigma\sigma'}^{N(F)} = Ad_{F(N)}D^{F(N)}(\varepsilon_F)T_{\sigma\sigma}T_{\sigma'\sigma'}^*$, A is the junction area, $d_{F(N)}$ is the thickness of F(N)-electrodes, $D^{F(N)}(\varepsilon_F)$ is the electron density of states at the Fermi energy ε_F . The tunneling rates $\Gamma_{\sigma\sigma'}^{N(F)}$ are related to the interface transparency $\mathcal{D}(\cos\beta)$ and to the spin-dependent interface resistance $R^{\sigma\sigma'}$ as

$$\begin{aligned}\Gamma_{N(F)}^{\sigma\sigma'} &= \frac{\hbar v_F}{4\pi Ad_{N(F)}} \int_0^1 x \mathcal{D}(x) dx = \\ &= \frac{\hbar}{4\pi e^2 Ad_{N(F)} D_{N(F)}^{\sigma\sigma'}(\varepsilon_F) R^{\sigma\sigma'}},\end{aligned}\quad (16)$$

where $x = \cos\beta$ and β is the angle of electron incidence. A typical magnitude of the tunneling rate Γ_F from N to F may be evaluated as $\Gamma_F \simeq 2.6 \cdot 10^{-4}$ eV, where we used N as Al, $\varepsilon_F = 11.63$ eV, the Al spacer thickness $d_N = 10^{-9}$ m, the area of the N/F junction $A = 10^{-6} \cdot 10^{-6}$ m, and the tunneling matrix element $T = 3 \cdot 10^{-6}$ eV. Such parameters correspond to the barrier transparency $\mathcal{D}(\cos\theta) = 10^{-2} \cos^2\theta$. The self-energy is expanded as

$$\hat{\Sigma}^R(\varepsilon) = [Z_\varepsilon - 1] \varepsilon \hat{\sigma}_3 + \phi i \hat{\sigma}_2, \quad (17)$$

where Z_ε describes the renormalization of the electron excitation spectrum, whereas ϕ concerns the tunneling-induced Zeeman splitting. We neglect by spin-flip processes during the tunneling (but assume that they take place inside the leads) and perform the summation over \mathbf{p}' as

$$\sum_p \hat{A}_{p,\varepsilon}^N = \Omega_N D^N(\varepsilon_F) \frac{Z_\varepsilon^N \varepsilon \hat{\sigma}_3 + \phi_N i \hat{\sigma}_2}{\sqrt{[Z_\varepsilon^N \varepsilon]^2 + \phi_N^2}} \quad (18)$$

where $\Omega_N = Ad_N$, $\phi_N = h_N \sin\theta_N$ and $Z_\varepsilon^N = 1 + h_N \cos\theta_N/\varepsilon$. Using the above formulas (14), (15), and (17), we obtain the coupled nonlinear self-consistent equations for the molecular field parameters $\Xi_N = \varepsilon h_N \sin\theta_N/[\varepsilon + h_N \cos\theta_N]$ and $\Xi_F = \phi_F/Z_\varepsilon^F$ in a nanoscopic junction as

$$\Xi_N = \frac{\left(h_N^{(i0)} \sin\theta_N + i\pi \Gamma_{\uparrow\downarrow} \frac{\Xi_F}{\zeta_\varepsilon^F} \cos\theta_N\right)}{\left[1 + \frac{h_N^{(i0)}}{\varepsilon} \cos\theta_N + i\pi \left(\frac{\Gamma_{\uparrow\downarrow}}{\zeta_\varepsilon^F} + \frac{\Xi_F}{\varepsilon} \frac{\Gamma_{\uparrow\downarrow}}{\zeta_\varepsilon^F} \sin\theta_N\right)\right]}, \quad (19)$$

$$\Xi_F = \frac{i\pi \frac{\Gamma_{\uparrow\downarrow} \Xi_N}{\zeta_\varepsilon^N} \cos\theta_N}{\left[1 + \frac{h_F^{(i0)}}{\varepsilon} + i\pi \left(\frac{\Gamma_{\uparrow\downarrow}}{\zeta_\varepsilon^N} + \frac{\Gamma_{\uparrow\downarrow}}{\zeta_\varepsilon^N} \frac{\Xi_N}{\varepsilon} \sin\theta_N\right)\right]}, \quad (20)$$

where $\zeta_\varepsilon^{N(F)} = \sqrt{\varepsilon^2 + \Xi_{N(F)}^2}$ while $\mathbf{h}_{N(F)}^{(i0)}$ are secondary intrinsic molecular fields defined below. The molecular field parameters Ξ_N and Ξ_F in Eqs. (19), (20) are finite only when the magnetization in the N/F-sandwich is twisted, i.e., $\theta_N \neq 0$. From Eqs. (19), (20) one can see that $\Xi_N(\varepsilon)$ and $\Xi_F(\varepsilon)$ are complex functions of the energy variable ε . The function $\Xi_F(\varepsilon)$ entering Eqs. (19), (20) describes a feed-back influence of N to F, when a twisted molecular field is induced also in F, in addition to its own primary equilibrium field $h_F^{(i0)}$. It means that spin-polarized electrons after the tunneling from F to N influence the electron excitation spectrum of N. The whole process is taken into account self-consistently on the basis of the above Eqs. (19) and (20). One can see, that the above proximity magnetization $\Xi_N \neq 0$ is effective either if $h_N^{(i0)} \neq 0$ or when $\Xi_F \neq 0$. The quantum kinetic equation is obtained in this paper by means of the Keldysh approach [16]. The mentioned diagram technique [16] operates with Green functions in the form of matrices 4×4 . According to [16], the Keldysh–Green function matrix components contain the information on the electron excitation spectrum (in the 2×2 submatrix functions $\hat{G}^{R(A)}$) and on the nonequilibrium distribution function (in the 2×2 submatrix function \hat{G}^K). Using the Keldysh approach [16], one obtains a kinetic equation in the form

$$i \text{Tr} \left\{ \frac{\partial \hat{g}^K}{\partial t} + v_F \mathbf{n} \hat{\sigma}_3 \frac{\partial \hat{g}^K}{\partial \mathbf{R}} \right\} = I_T^s + S_{sf}, \quad (21)$$

where \mathbf{n} is a unit vector in the direction of the electron momentum. In Eq. (21), \hat{g}^K is the Keldysh submatrix function integrated over the kinetic energy ζ_p .

$$\begin{aligned}I_T^s &= L_{\varepsilon,\varepsilon-V}^{(1)} (f_{1,\varepsilon} - f_{1,\varepsilon-V}) + \\ &+ L_{\varepsilon,\varepsilon-V}^{(2)} (f_{2,\varepsilon} - f_{2,\varepsilon-V})\end{aligned}\quad (22)$$

where the „coherent factors“ in N are

$$\begin{aligned}L_{\varepsilon,\varepsilon-V}^{(1)} &= 4\pi (\Gamma_2 \varepsilon (\varepsilon - V) + \Gamma_1 \varepsilon \Xi_F \sin\theta + \\ &+ \Gamma_4 \Xi_F \Xi_N \cos\theta) / (\zeta_{\varepsilon-V}^F \zeta_\varepsilon^N)\end{aligned}\quad (23)$$

$$\begin{aligned}L_{\varepsilon,\varepsilon-V}^{(2)} &= 4\pi (\Gamma_1 \varepsilon (\varepsilon - V) + \Gamma_2 \varepsilon \Xi_F \sin\theta + \\ &+ \Gamma_3 \Xi_F \Xi_N \cos\theta) / (\zeta_{\varepsilon-V}^F \zeta_\varepsilon^N)\end{aligned}\quad (24)$$

where θ is the twisting angle between the quantization axes in N and in F. In Eqs. (23) and (24), the bias voltage V is expressed in energy units.

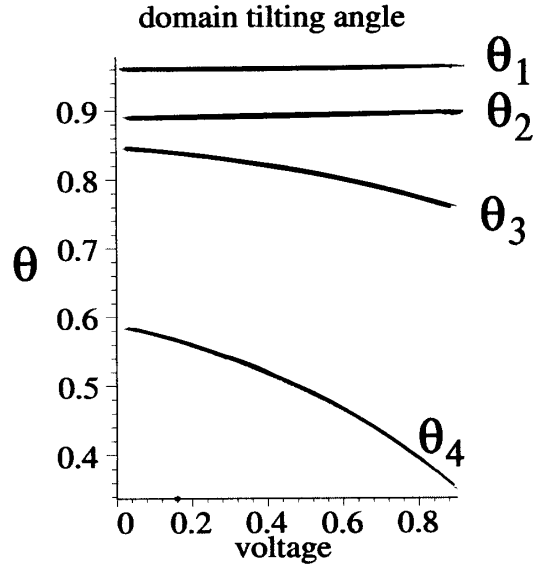


Fig. 2. Influence of the bias voltage V on the domain's tilting angle θ . One can infer that the induced molecular fields \mathbf{h}_N are non-collinear to the driving intrinsic field \mathbf{h}_F in F

The illustrative analysis of the magnetic properties induced in N is based on Eqs. (19)–(24). Let us consider a nonequilibrium quasistationary situation when the bias voltage $V = \text{const}$ is applied across the N/F sandwich. In that case, one sets $\partial f_{2,\varepsilon}/\partial t \simeq 0$. Solving the system of non-linear equations, one finds four positive and four negative roots ζ_i and 2 roots $h_N^{(1,2)}$. The multiple roots correspond to an instability in the system with induced magnetization. Such an instability is interpreted as the appearance of domains characterized by their tilting angle $\theta_i = \arccos \zeta_i$ and by their magnitude of the induced molecular field $h_N^{(i)}$ inside each domain. The bias voltage V influences the domain structure drastically.

It becomes evident from the plots in Figs. 2 and 3 where the solutions for the tilting angle θ_i and $h_N^{(i)}$ of each i -th domain are shown. In particular, Fig. 3 shows how θ_i depends on the bias voltage V . In all the domains, the tilting angle θ_i is essentially finite, i.e., $0 < \theta_i < \pi/2$. This means that, in the case considered, the induced molecular field \mathbf{h}_N is non-collinear to the driving intrinsic field \mathbf{h}_F in F. In addition, as follows from Fig. 2, θ_i in some domains changes versus V (the rotation of $h_N^{(i)}$ as V grows), while θ_i remains steady in other domains. The magnitude $h_N^{(i)}$ of the induced molecular field presented in Fig. 3 depends on V in an unusual way. In particular, as follows from the mentioned Fig. 3, $h_N^{(i)}$ diminishes as V grows. Such anomalous behavior is

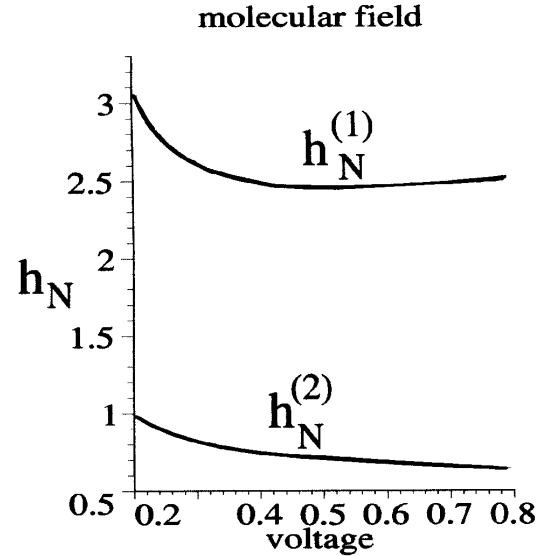


Fig. 3. Induced molecular field $h_N^{(i)}$ versus the bias voltage across the N/F sandwich. Such anomalous behavior (i.e., $h_N^{(i)}$ diminishes as V grows) is caused by the shape of the spin imbalance distribution function $f_{2,\varepsilon}$ that has a maximum at finite energies

explained by the shape of the spin imbalance distribution function $f_{2,\varepsilon}$ that has a maximum at low but finite energies. Because the N and F spacers are thin ($d_{N(F)} \leq \xi_{sf}$), the magnetization across each spacer is roughly homogeneous, and the domain size cannot fit the film thickness. But in junctions with sufficiently big cross-section area, i.e. $A \gg \xi_{sf}^2$, the domains are positioned in leads along the N/F interface.

An experimental setup for the observation of the nonequilibrium spin magnetization may be based on non-symmetric tunneling M-I-N/F devices, where M is a metal electrode attached to the N/F sandwich. The transparency of the left potential barrier I is assumed to be much lower as compared to the transparency of the N/F interface. The bias voltage V may be applied either across the whole double barrier system, or to its parts separately. In such a device, the influence of M to N is negligible as compared to the coupling between N and F. The mentioned setup would allow one to conduct the tunneling spectroscopy of the electron excitation spectrum in N. The spectral features coming from the induced domain structure will be manifested in the curves of differential tunneling conductivity $dI(V)/dV$ across the whole M-I-N/F device.

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1. Miyazaki T., Tezuka N. // J. Magn. Magn. and Mater. **139**, L231 (1995); Moodera J.S., Kinder L.R., Wong T.M., Meservey R. // Phys. Rev. Lett. **74**, 3273 (1995); Moodera J.S., Kinder L.R. // J. Appl. Phys. **79**, 4724 (1996).
2. Ingvansson S., Xiao G., Parkin S.S.P. et al. // Phys. Rev. Lett. **85**, 3289 (2000).
3. Gallagher W.J., Parkin S.S.P., Yu Lu et al. // J. Appl. Phys. **81**, 3741 (1997).
4. Johnson M., Silsbee R.H. // Phys. Rev. Lett. **55**, 1790 (1985).
5. Aronov A.G. // Sov. Phys. JETP, **44**, 193 (1976).
6. Johnson M. // Appl. Phys. Lett. **65**, 1460 (1994).
7. Brataas A. et al. // Phys. Rev. **B59**, 93 (1999); Barnas J., Fert A. // Europhys. Lett. **44**, 85 (1998); Korotkov A.N., Safarov V.I. // Phys. Rev. B **59**, 89 (1999); H. Imamura et al. // Ibid. **59**, 6017 (1999).
8. Jullière M. // Phys. Lett. **54**, 225 (1975); Maekawa S., Gafvert U. // IEEE Trans. Magn. **18**, 707 (1982).
9. Slonczewski J.C. // Phys. Rev. B **39**, 6995 (1989).
10. Grünberg P., Schreiber R., Pang Y. et al. // Phys. Rev. Lett. **57**, 2442 (1986).
11. d'Albuquerque e Castro J., Mathon J., Villeret M., Edwards D.M. // Phys. Rev. B **49**, 16 062 (1994).
12. Bruno P. // Ibid. **52**, 411 (1995).
13. Schwabe N.F., Wingreen Ned.S., Elliott R.J. // Phys. Rev. B **54**, 12 953 (1996); Heide C., Elliott R.J., Wingreen Ned.S. // Ibid. **59**, 4287 (1999-II).
14. Johnson M., Silsbee R.H. // Phys. Rev. **B37**, 5321 (1988); Johnson M., Silsbee R.H. // Ibid. **37**, 5326 (1988).
15. van Son P.C., van Kempen H., Wyder P. // Phys. Rev. Lett. **58**, 2271 (1987).
16. Keldysh L.V. // Sov. Phys. JETP, **20**, 1018 (1965).
17. Cohen M.H., Falicov L.M., Phillips J.C. // Phys. Rev. Lett. **8**, 316 (1962).
18. McMillan W.L. // Phys. Rev. **165**, 746 (1968).
19. Landau L.D., Livshits E.M. Electrodynamics of Continuous Media. — Moscow: Nauka, 1982 (in Russian).
20. Bulzhenkov I.E., Ivlev B.I. // Zh. Eksp. Teor. Fiz. **74**, 224 (1978) [Sov. Phys. JETP **47**, 115 (1978)].
21. Elesin V.F., Kopaev Yu.V. // Uspekhi Fiz. Nauk **133**, 259 (1981).
22. Gurevich A.G., Melkov D.A. Magnetization Oscillations and Waves. — Boca Raton: CRC Press, 1996.
23. Valet T., Fert A. // Phys. Rev. B **48**, 7099 (1993-II).

ТУНЕЛЬНО-НАВЕДЕНЕ НАМАГНІЧУВАННЯ В САНДВІЧ-СТРУКТУРАХ НОРМАЛЬНИЙ МЕТАЛ/ФЕРОМАГНІТ

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Резюме

Досліджено механізм намагнічування завдяки тунелюванню в сандвіч-структурі нормальний метал/ферромагніт. Методом техніки Келдиша для нерівноважних процесів отримано нелінійні рівняння, які описують магнітні властивості компонентів структури. До них входять рівняння самоузгодження для внутрішніх молекулярних полів \mathbf{h}_N та \mathbf{h}_F , доповнені кінетичними рівняннями для функцій спінового розбалансування $f_{2,\varepsilon}$. Вивчаються: (i) магнетизація, наведена прямою тунельною взаємодією, та (ii) магнетизація за рахунок нерівноважного спінового розбалансування. Набір нелінійних рівнянь має декілька розв'язків, які відповідають доменам намагнічування, що виникають завдяки спін-поляризованому тунелюванню під дією напруги зміщення, прикладеної до сандвіча.

ТУННЕЛЬНО-НАВЕДЕННАЯ НАМАГНИЧЕННОСТЬ В САНДВИЧ-СТРУКТУРАХ НОРМАЛЬНЫЙ МЕТАЛЛ/ФЕРРОМАГНЕТИК

С.Е. Шафранюк

Резюме

Исследуется механизм намагниченности благодаря тунелированию в сандвич-структуре нормальный металл/ферромагнетик. Методом техники Келдыша для неравновесных процессов получены нелинейные уравнения, которые описывают магнитные свойства компонентов структуры. Сюда входят уравнения самосогласования для внутренних молекулярных полей \mathbf{h}_N и \mathbf{h}_F , дополненные кинетическими уравнениями для функции спинового разбаланса $f_{2,\varepsilon}$. Изучаются: (i) магнетизация, наведенная прямым туннельным взаимодействием, и (ii) магнетизация за счет неравновесного спинового разбаланса. Набор нелинейных уравнений имеет несколько решений, которые отвечают доменам намагниченности, возникающим благодаря спин-поляризованому тунелированию под воздействием напряжения смещения, приложенного к сандвичу.