Spin-polarized Current-induced Instability in Spin-Valve with Antiferromagnetic Layer

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Abstract

In the framework of phenomenological model we consider dynamics of a compensated collinear antiferromagnet (AFM) in the presence of spin-polarised current. The model is based on the assumption that AFM spins are localised and spin torque is transferred to each magnetic sublattice independently. It is shown that AFM spin current i) can be a source of the “negative friction”; and ii) modifies spin-wave frequencies. Equilibrium state of AFM can be destabilized by the current polarized in parallel to AFM vector. Threshold current at which the loss of stability takes place depends upon the magnetic anisotropy of AFM.

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I. INTRODUCTION

The phenomenon of spin transfer from conductivity electrons to magnetization of ferromagnetic (FM) layer is widely used in engineering of the magnetic memory devices. While flowing from nonmagnetic to ferromagnetic layer spin-polarised electrons transfer spin torque and additional magnetization thus inducing reorientation or even dynamically stable rotation of localised magnetic moments. Physical interpretation of these phenomena is based on the law of spin conservation and \( s - d \) exchange interaction between free carriers and localized moments.\(^1\)\(^3\)

Recent experiments with nanopillars\(^4\)\(^5\) point out that spin-polarised current also can change the state of antiferromagnetic (AFM) layer and characteristic value of critical current at which reorientation of spins takes place could be much smaller than in FM. From general point of view, study of spin transport effects in AFM may open either more efficient methods for spintronics or much more reach fundamental phenomena. In particular, in the AFM metal with spin-density waves (SDW) \( s - d \) exchange couples spins of free electrons with orientation of AFM vector and influence of spin torque is substantially enhanced.\(^6\)

In the present paper we address another question: “Is it possible to control the state of an AFM metal without SDW with spin-polarized current?” As a starting point we consider the “toy” model of the compensated collinear AFM in which the magnetic order is mainly caused by localised spins. \( \text{Fe}_{50}\text{Mn}_{50} \) alloy widely used in spin-valve structures can be considered as an example of such a material.

II. MODEL

We consider a spin-valve structure (analogous to that studied in Ref.\(^4\)\(^5\) consisting of FM and AFM layers separated by a nonmagnetic metallic spacer (Fig.\(\text{I}\)) rather thin in order to condition a ballistic regime for conductivity electrons. FM with an easy axis in \( p \) direction acts as a spin polarizer for the electron current \( I \) flowing through the whole structure. The magnetic state of AFM is unambiguously defined by sublattice magnetizations \( \mathbf{M}_j \) (\( j=1,2 \)). We assume that due to a local character of \( s - d \) exchange, spin conservation law is fulfilled independently for each act of conductivity-to-localized spin interaction.\(^7\) So, according to Slonczewskii mechanism\(^1\), each sublattice magnetization experiences a spin
torque $\mathbf{T}_j = \sigma I [\mathbf{M}_j \times (\mathbf{M}_j \times \mathbf{p})]/M_0$, where coefficient $\sigma = \varepsilon \eta \mu_0/(2M_0 Ve)$ depends upon the geometry of contact (volume $V$), and spin-polarization efficiency $\varepsilon$, $M_0 = |\mathbf{M}_j|$. Here $\eta$ is the Plank constant, $g$ is gyromagnetic ratio and $e$ is electron charge. Depending on the direction of the electron current the sign of $I$ can be either positive (incoming spin flux) or negative (outcoming spin flux).

In the present paper we restrict ourselves with the case of small external exposure, i.e., the work of the polarized current over the localized spins is supposed to be much smaller than the exchange energy that keeps magnetizations $\mathbf{M}_1, \mathbf{M}_2$ antiparallel. To this end, macroscopic magnetization $\mathbf{M} = \mathbf{M}_1 + \mathbf{M}_2$ is much smaller than AFM vector $\mathbf{L} = \mathbf{M}_1 - \mathbf{M}_2$, $|\mathbf{M}| \ll |\mathbf{L}|$, and one can reduce the description of AFM dynamics to a Lagrange form with $\mathbf{L}$ as a generalized variable and the Lagrange function in a form $^8$

$$L = \frac{\chi_\perp}{8g^2 M_0^2} \dot{\mathbf{L}}^2 - \frac{A}{8M_0^2} (\nabla \mathbf{L})^2 - w_{an}(\mathbf{L}). \quad (1)$$

Here $\chi_\perp$, $A$, and $w_{an}(\mathbf{L})$ are the magnetic susceptibility, inhomogeneous exchange constant and magnetic energy of AFM layer, respectively.

Within the framework of the Lagrange formalism, all the dissipative processes (Gilbert damping and spin-torque induced rotation of magnetic moments) could be adequately de-
scribed with the Relay function

\[ R = \frac{\chi_{\perp}\alpha G}{8g^2M_0^2} \dot{L}^2 - \frac{\sigma I}{4gM_0}(p, L \times \dot{L}), \]  

(2)

where the damping parameter \( \alpha_G \) is equal to the linewidth of AFM resonance (see, e.g., Ref. 9).

III. GENERAL CONSIDERATIONS

Some peculiarities of AFM dynamics in the presence of spin-polarized current can be deduced from the analysis of the Relay function (2) that describes the rate of energy losses in the system.

- **Like** in FM, spin-polarized current may work as a source of the external energy pumping (“negative” friction) and suppress the Gilbert damping. This takes place for a certain value of current, \( I \geq I_{c1} \), and noncollinear orientation of FM and AFM easy axes, e.g., \( p \perp L^{(0)} \). Critical current \( I_{cr} \) at which the effective damping changes sign is calculated from the condition of negative dissipation \( \dot{L}(\partial R/\partial \dot{L}) \leq 0 \). In the case of steady precession of AFM vector with a frequency \( \omega \) around the equilibrium direction \( L^{(0)} \), the critical current is given by the expression \( I_{cr} \propto \chi_{\perp}\alpha G\omega/\sigma \), analogous to that in FM material.\(^\text{10}\)** In contrast to** FM, the value of critical current in AFM is substantially reduced due to strong exchange interaction between the magnetic sublattices (AFM susceptibility \( \chi_{\perp} \) is small).

- An efficient energy pumping takes place for the precessional motion only, i.e., when \( L \perp \dot{L} \). Linear oscillations of AFM vector (with \( L \parallel \dot{L} \)) are always dissipative, \( \dot{L}(\partial R/\partial \dot{L}) \geq 0 \).

- **Unlike** FM, the presence of spin-polarized current may change spin-wave spectra of AFM and thus give rise to instability and a kind of spin-flop transition in the case when FM and AFM easy axes are parallel, \( p \parallel L^{(0)} \). As can be seen from (2), small deviations \( \delta L_{\perp} \perp L^{(0)} \) oriented perpendicular to equilibrium vector \( L^{(0)} \) induce a generalized force \( F = -\partial R/\partial \dot{L} = p \times \delta L_{\perp}(I \sigma/4gM_0) \). This force is a linear function of \( \delta L_{\perp} \) and thus may compete with the restoring force produced by the magnetic anisotropy field.

In the next section we consider the last case in more details.
IV. CURRENT-INDUCED INSTABILITY

The typical AFM metal used in spin-valves can be thought of as an “easy-plane” AFM because of \(i\) a very small anisotropy of bulk materials and \(ii\) possible out-of-plane anisotropy produced by the shape and interfacial interactions. Let equilibrium orientation of AFM vector \(L(0)\) be parallel to FM magnetization \(p\parallel Z\) in the film plane. In this case the linearized Lagrange equations for small excitations \(L_x, L_y\) are obtained from (1), (2) as follows:

\[
\ddot{L}_x + \alpha_G \dot{L}_x - c^2 \nabla^2 L_x + \omega_x^2(0)L_x - \sigma I g M_0 \chi^{-1}_\perp L_y = 0,
\]

\[
\ddot{L}_y + \alpha_G \dot{L}_y - c^2 \nabla^2 L_y + \omega_y^2(0)L_y + \sigma I g M_0 \chi^{-1}_\perp L_x = 0,
\]

(3)

where the gaps \(\omega_j(0) = g\sqrt{K_j/\chi_\perp}\), \((j = x, y)\) in spin-wave spectra are expressed through the effective anisotropy constants \(K_x, K_y, c = g\sqrt{A/\chi_\perp}\) is a spin-wave velocity, \(X\) axis is directed perpendicular to the film plane.

The analysis of shows that depending on the current value \(I\) equations (3), have two types of solutions. Below the threshold \(I \leq I_{th1} \equiv g|K_x - K_y|/(2M_0\sigma)\) AFM vector oscillates around equilibrium direction with eigenfrequencies

\[
\Omega_{1,2}^2(k) = \frac{1}{2} \left(\omega_x^2 + \omega_y^2\right) + c^2 k^2 \pm \frac{1}{2} \left(\omega_x^2 - \omega_y^2\right) \sqrt{1 - \left(I/I_{th1}\right)^2},
\]

(4)

where \(k\) is wave-vector. Both modes are linearly polarized. The greater the current, the greater is the out-of-plane component \(L_x\). Energy dissipation is due to internal friction solely and thus, equilibrium state with \(L(0)\parallel p\) is stable.

With increase of \(I\) the difference between the frequencies \(\Omega_1, \Omega_2\) decreases until at \(I = I_{th1}\) the spectrum became degenerate, \(\Omega_1 = \Omega_2\). Polarization of eigen modes can be either linear or circular and energy dissipation is governed by two mechanisms: damping and pumping. In the interval \(I_{th1} \leq I \leq I_{th2} \equiv \sqrt{I_{th1}^2 + I_{cr}^2}\) damping is stronger that pumping and the state with \(L(0)\parallel p\) is stable. The value of critical current

\[
I_{cr} = \frac{\alpha_G \sqrt{K_y \chi_\perp}}{2M_0\sigma} = \frac{\alpha_G}{\omega_y(0)} \frac{K_y}{K_x - K_y} I_{th1}
\]

(5)

is calculated from the condition of accurate compensation of two dissipation mechanisms. For definiteness we assume that in-plane anisotropy \(K_y\) is weaker than out-of-plane \(K_x\).

At \(I \geq I_{th2}\) an amplitude of at least one of the modes grows exponentially with the current-dependent increment \(\alpha = \alpha_G(I - I_{th2})/I_{cr}\). This means that the state with \(L(0)\parallel p\)
becomes unstable and the system evolves to a new state, e.g. to another (nonparallel to \(p\)) equilibrium orientation of AFM vector in the film plane. Such a behaviour is somehow analogous to spin-flop transition observed in AFMs of the “easy-plane” type under the action of external magnetic field applied in parallel to AFM vector.

V. DISCUSSION

The described dynamics of AFM in the presence of spin-polarised current differs substantially from that in FM materials. The difference can be intuitively understood from the geometry of spin rotation (see Figs 2 and 3). In the FM characterised by a single magnetic vector \(M\) magnetization has only two degrees of freedom. In the absence of any dissipative processes magnetic excitations take a form of precessional motion of \(M\) around its equilibrium direction \(M_0\) (double-line ellipse in Fig 2). The motive force of the precession is an effective internal field that keeps magnetization direction along an easy axis \(M_0\) (in the particular case, parallel to spin polarisation axis \(p\)). Spin torque \(T\) acts in such a way as to change an angle between \(M\) and \(M_0\), and, correspondingly, energy of excitation. Thus, in FM spin torque always acts as an energy source (or drain) and thus its effect is equivalent to positive/negative friction. Nondissipative dynamics in FM is possible only in the case of precise balance between the torque-induced pumping and internal damping.

![Figure 2: (Color online) Rotation of magnetization M under the action of spin torque.](image)

AFM with two magnetic sublattices has more degrees of freedom. In the absence of dissipation the low-energy excitations correspond to coherent precession of both sublattice magnetizations \(M_1\) and \(M_2\) (double-line ellipses in Fig 3). The effective internal fields rotate
magnetizations in opposite directions so that an AFM \( \mathbf{L} \) vector can oscillate within a plane.

Spin torques \( \mathbf{T}_1 \) and \( \mathbf{T}_2 \) turn both magnetizations \( \mathbf{M}_1 \) and \( \mathbf{M}_2 \) in the same direction ("up" in Fig 3).

![Figure 3: (Color online) Rotation of sublattice magnetizations \( \mathbf{M}_{1,2} \) and AFM vector \( \mathbf{L} \) under the action of spin torques \( \mathbf{T}_{1,2} \).](image)

So, for one sublattice an angle between the excited and equilibrium orientations increases and for another sublattice decreases. This means that for a certain relation between spin current and internal field (defined by the magnetic anisotropy constants \( K_{x,y} \)) corresponding changes in energy could be totally compensated and torque-induced motion is nondissipative even in the absence of the internal damping.

The described ("nondissipative") influence of spin-current on AFM below the threshold current \( I < I_{th1} \) is to a certain extent analogous to the affect of an external magnetic field applied in parallel to \( \mathbf{L}^{(0)} \). Both the magnetic field and spin-current may give rise to the softening of one of the spin-wave modes and cause spin-flop transition or transition to dynamically stable stationary state. Each effect is insensitive to the reversal of field direction, spin polarization and current direction. On the contrary, due to the difference of symmetry properties and depending on mutual orientation of field, spin and current flow,
combined application of the magnetic field and spin-polarized current, may give rise to an enhancement or to reduction of threshold current and spin-flop field. Detailed analysis of this situation is beyond the scope of the paper.

The dynamics obtained in the framework of a very simple “toy” model is nevertheless qualitatively consistent with the observed\textsuperscript{5} direct effect of electron current on the magnetic state of FeMn, namely, irreversible switching of spin-valve structure at a threshold current $I \propto 5 \div 7.5$ mA. The effect was observed in the presence of the external magnetic field $H \propto 0.1$ T. The authors attributed this behavior to “reorientations of magnetic configuration of FeMn among a few metastable states”. We think that the reason of reorientation can be the current-induced instability described above. External field applied in-parallel to $\mathbf{L}^{(0)}$ is a source of additional magnetic anisotropy.

The value of threshold current can be roughly estimated using the value of FeMn bulk susceptibility\textsuperscript{11} $\chi_\perp = 10^{-5}$ (SI units), magnetization $2\mu_0M_0=0.1$ T and typical AFM layer dimensions\textsuperscript{5} 120x60x1.5 nm$^3$. We assume that out-of-plane anisotropy $K_x$ can be as large as $10^5$J/m$^3$ due to the interface effects (e.g., coupling strength between Co/FeMn layers is estimated\textsuperscript{12} as $10^{-4}$ J/m$^2$ and monolayer thickness is $\propto 3 \cdot 10^{-10}$ m). Ultimately, in the case of 100% spin-polarization efficiency, we get $I_{th1} \propto K_x V e/\eta \propto 10$ mA. Threshold current $I_{th2}$, which separates reversible/irreversible rotation of vector $\mathbf{L}$ is of the same order of value, at least in the case of the pronounced anisotropy ($K_x-K_y \propto K_y$) and quality factor of AFM resonance $\omega_y/\alpha_G \geq 10$. Really, in this case, as follows from \textsuperscript{5}, critical current $I_{cr} \leq 0.1I_{th1}$ and $I_{th2} \approx I_{th1} \propto 10$ mA that agrees in order of value with experimental results.

\textbf{VI. CONCLUSIONS}

In summary, we have considered the dynamics of a compensated AFM with localized spins in the presence of spin-polarized current. In contrast to FM, spin current is not only a source of “negative friction” but it also acts as an “effective field” that modifies spin-wave modes and gives rise to the loss of stability of the state with parallel orientation of spin polarization and AFM vector. Predictions of the above “toy” model are in qualitative agreement with experimentally observed influence of spin current on AFM FeMn. Estimated values of the threshold current are of the same order of value as characteristic currents in the experiment\textsuperscript{5}.
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