EFFECTS INDUCED BY SPIN-POLARIZED CURRENT IN ANTIFERROMAGNETS

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Goal: to study the effect of spin-polarized current on the magnetic state of antiferromagnet

Motivation

We **know** that:

1. Spin-polarized electrons transfer spin torque [1] and additional magnetization [2] to thin ferromagnetic (FM) layer thus producing switching or stable precession of magnetization.
2. The value of electric resistance depends upon the mutual orientation of two FM layers (GMR effect)
3. The presence of antiferromagnet (AFM) affects the dependence of GMR versus current and magnetic field value (experiments [3-5]).

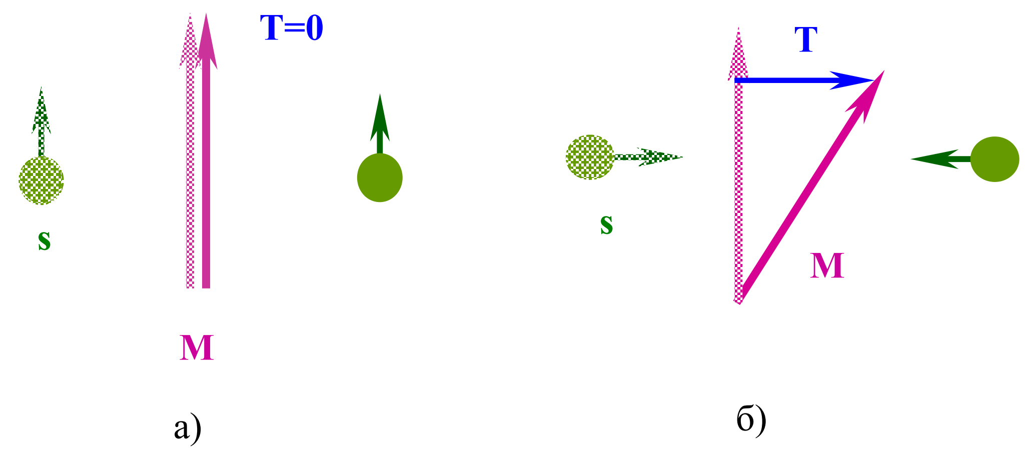
We **do not** know:

1. How to **describe the dynamics** of AFM in the presence of spin-polarized current?
2. What **effects** could be observed?
3. Is there any **difference** between AFM and FM?
4. Could **AFM** materials produce GMR effect (see [5])?

Spin torque in FM (Slonczewski, Berger, [1]**)**

Dynamics of FM in the presence of spin-polarized current [6]:

$$\dot{\mathbf{M}} = g[\mathbf{M}\times\mathbf{H}_M] + \alpha_G[\mathbf{M}\times\dot{\mathbf{M}}] + \sigma I[\mathbf{M}\times[\mathbf{M}\times\mathbf{p}_{\mathrm{cur}}]] \quad (1)$$



Nature of spin torque: a) free electron is polarized in parallel to local magnetic moment **M** – no spin scattering, no spin torque; b) free electron is polarized perpendicular to local magnetic moment **M**, spin scattering induces rotation of **M** (conservation of total spin moment), spin torque **T** is parallel to Δ**M**.

Assumptions

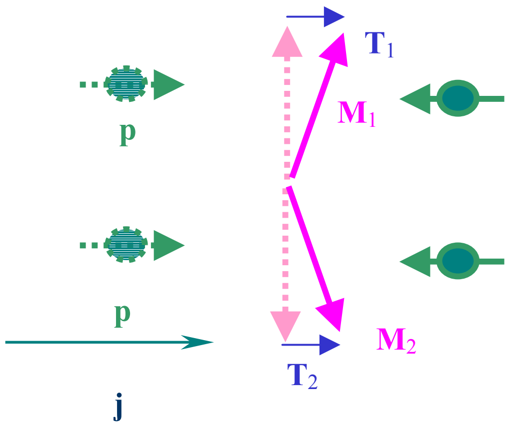
In **AFM**

- AFM order is formed by **localized** magnetic moments;
- interaction between the conduction electrons and localized spins (*s-d* exchange) is **short-range**;
- free AFM layer is described by macrospins (sublattice magnetizations $\mathbf{M}_k$).

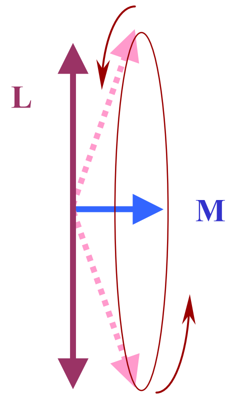
Model

Dynamics of each macrospin $\mathbf{M}_k$ is described by LLG equations of type (1). For the collinear AFM with strong exchange coupling ($\mathbf{M}=\mathbf{M}_1+\mathbf{M}_2 \ll \mathbf{L}=\mathbf{M}_1-\mathbf{M}_2$) dynamics of AFM vector can be reduced to equation (a la [7]):

$$\ddot{\mathbf{L}}\times\mathbf{L} = \frac{g^2}{\chi_\perp}[\mathbf{L}\times\mathbf{H}_L] + \frac{g\alpha_G}{\chi_\perp}[\mathbf{L}\times\dot{\mathbf{L}}] + \frac{g\sigma I}{\chi_\perp}[\mathbf{L}\times[\mathbf{L}\times\mathbf{p}_{\mathrm{cur}}]] \quad (2)$$

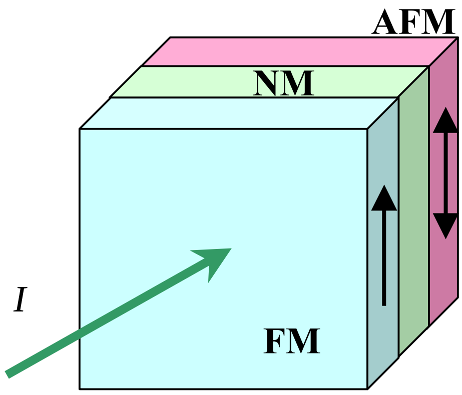


Spin torques $\mathbf{T}_{1,2}$. acting on the sublattices magnetizations $\mathbf{M}_{1,2}$ from the spin-polarized current.

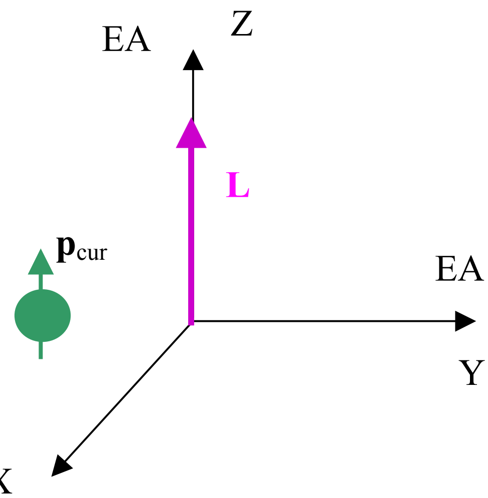


Dynamics of AFM vector

Sample geometry



3-D scheme of heterostructure, positive current *I* flows from FM to AFM layer



Equilibrium state, spin polarization $\mathbf{p}_{\mathrm{cur}}$ of current is parallel to easy axis (EA) of AFM

Lagrange approach

The dynamics of AFM in the presence of spin-polarized current can be analyzed within Lagrange formalism with the Lagrange function

$$L = \frac{\chi_\perp}{8g^2 M_0^2}\dot{\mathbf{L}}^2 - \frac{A}{8M_0^2}(\nabla \mathbf{L})^2 - w_{\mathrm{an}}(\mathbf{L}), \qquad (3)$$

and dissipation (Rayleigh) function

$$R = \frac{\chi_\perp \alpha_G}{8g^2 M_0^2}\dot{\mathbf{L}}^2 - \frac{\sigma I}{4gM_0}(\mathbf{p}_{\mathrm{curr}}, \mathbf{L}\times\dot{\mathbf{L}}). \qquad (4)$$

Magnetic anisotropy of AFM (example, “easy-plane” type):

$$w_{an} = -\frac{1}{2}K_2 L_x^2 - \frac{1}{4}K_4\left(L_x^4 + L_y^4 + L_z^4\right) \qquad (5)$$

Equations of motion

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{\mathbf{L}}} - \frac{\partial L}{\partial \mathbf{L}} = -\frac{\partial R}{\partial \dot{\mathbf{L}}} \qquad (6)$$

Effects

1. **Positive/negative friction**: like in FM, spin-polarized current can compete with internal dissipation (2-d term in (4)).
2. **Shift of AFMR frequencies & current-induced spin-flop:** If $\mathbf{p}_{\mathrm{cur}}$ is parallel to EA of AFM, spin-wave spectra are current-dependent:

$$\Omega_{1,2}^2(\mathbf{k}) = \tfrac{1}{2}\left(\omega_x^2 + \omega_y^2\right) + c^2\mathbf{k}^2 \pm \tfrac{1}{2}\left(\omega_x^2 - \omega_y^2\right)\sqrt{1-(I/I_{\mathrm{th1}})^2}, \qquad (7)$$

where $\omega_j(0) = g\sqrt{K_j/\chi_\perp}$ are AFMR frequencies (j=x, y). In contrast to FM, spin current works as **nondissipative force and** renormalizes AFMR frequencies!

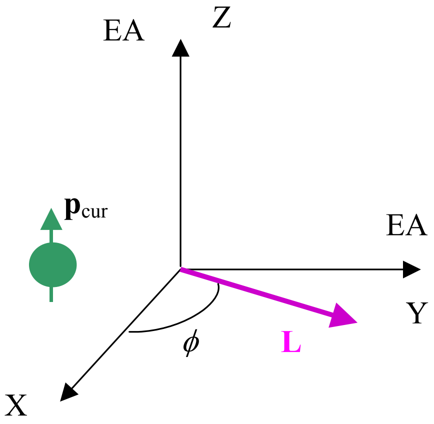
The critical current of destabilization depends upon **magnetic anisotropy** (in FM –by relaxation constant only):

$$I \le I_{\mathrm{th1}} \equiv g|K_x - K_y|/(2M_0\sigma). \qquad (8)$$

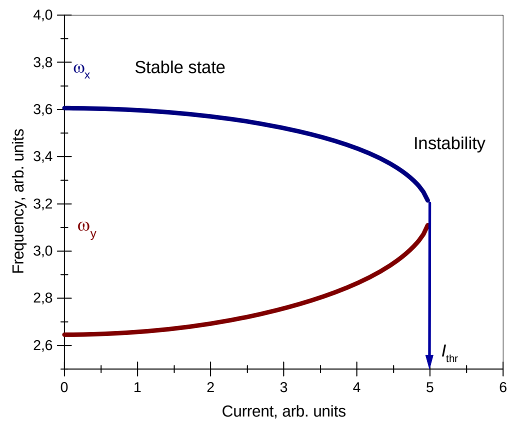
Corrections from relaxation (parameter α_G):

$$I = \sqrt{I_{\mathrm{th1}}^2 + I_{\mathrm{cr}}^2},\ I_{\mathrm{cr}} \equiv \frac{\alpha_G\sqrt{K_y\chi_\perp}}{2M_0\sigma} = \frac{\alpha_G}{\omega_y(0)}\frac{K_y}{K_x - K_y}I_{\mathrm{th1}} \qquad (9)$$

3. **Spin-flop state:** for 4-fold anisotropy (see (5)) another stable state exists with $\phi = \frac{1}{4}\arcsin(I / I_{\text{thr}}), I_{\text{thr}} = K_4 g / (M_0 \sigma)$.



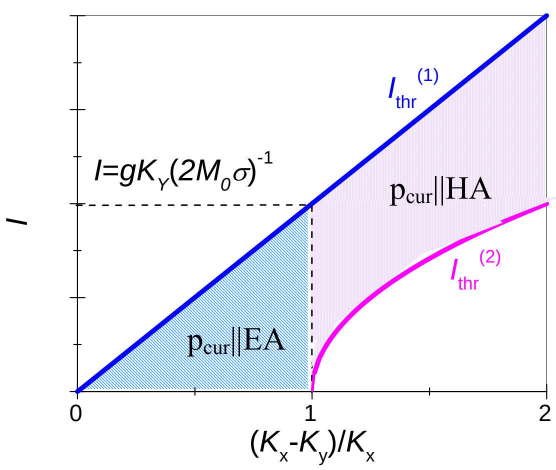
Spin-flop state, current induces rotation of AFM vector from EA



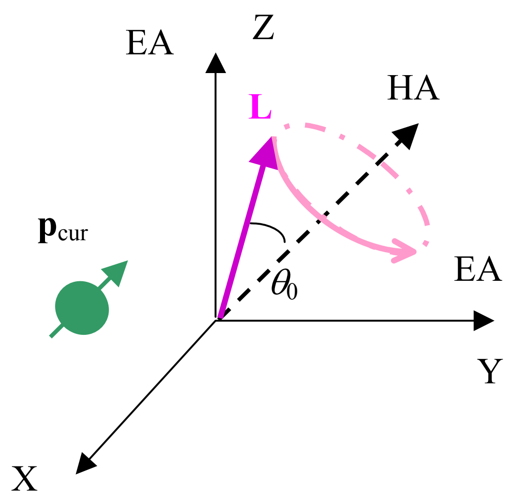
Spin-wave frequency (in long-wave limit) vs current

4. **Spin Transfer Oscillator**: like in FM, stable rotation of AFM vector can be stimulated by spin transfer when $\mathbf{p}_{\text{cur}}$ is parallel to "hard" axis (HA). In **contrast** to FM, critical current depends on magentic anisotropy

$$I \geq I_{\text{thr}}^{(2)} \equiv g\sqrt{|K_y| K_x} / (2M_0 \sigma) \qquad (10)$$



"Phase" diagram in coordinates current–relative magnetic anisotropy



Dynamically stable state (spin transfer oscillator), $\theta_0(I)$

5. **Parametric downconversion:** ac current can induce parametric resonance:

$$\ddot{L}_x + \alpha_G \dot{L}_x - c^2\nabla^2 L_x + \omega_x^2(0) L_x = I_0 \cos\omega t(\sigma g M_0 \chi_\perp^{-1}) L_y, \quad (11)$$

$$\ddot{L}_y + \alpha_G \dot{L}_y - c^2\nabla^2 L_y + \omega_y^2(0) L_y = -I_0 \cos\omega t(\sigma g M_0 \chi_\perp^{-1}) L_x, \quad (12)$$

In anisotropic AFM the lowest resonance frequency can be as small as $\omega_{\mathrm{res}} = |\omega_x(0) - \omega_y(0)|$. Resonance width increases with the current amplitude:

$$\Delta\omega_{\mathrm{res}} = \sqrt{\omega_x \omega_y \left[\left(I_0 / I_{cr} \right)^2 - 1 \right]},\ I_{cr} \equiv (\alpha_G / \sigma)\sqrt{\omega_x \omega_y} \quad (13)$$

Comparison with experiment

Potential candidates for AFM layer:
FeMn, IrMn (collinear AFM in epitaxial films), $FePt_3$;
Mn_3NiN, Mn_3AgN, Mn_3GaN (noncollinear AFM)

Typical parameters:
susceptibility $\chi_{\perp}=10^{-5}$ (SI units)
magnetization $2\mu_0 M_0$=0,1 T
anisotropy $K_x = 10^5$ J/m^3, $|K_x - K_y| \propto K_x$
quality factor of resonance (inverse damping parameter) 0.1.
Expected threshold field $I_{th1} \propto$ 10 mA.
Experiments [3,4] $I \propto 5 \div 7.5$ mA.

All the dynamical effects (e.g., eigenfrequencies of spin waves, etc) **in AFMs** are **amplified** (compared to FM) due to exchange coupling between sublattices. So, for the AFM and FM samples with comparable values of resonance frequencies the ratio of corresponding threshold currents

$$I_{\mathrm{thr}}^{\mathrm{AFM}} / I_{\mathrm{thr}}^{\mathrm{FM}} = H_A / \mu_0 M_0^{\mathrm{FM}}$$

is proportional to AFM anisotropy field $H_A \leq 0.03$ T, while $\mu_0 M_0^{\mathrm{FM}} \propto 0,3 \div 1$ T, so, $I_{\mathrm{cr}}^{\mathrm{AFM}} \langle\langle\, I_{\mathrm{cr}}^{\mathrm{FM}}$.

Conclusions:

1. AFMs can show new (compared with FMs) spin dynamics in the presence of spin-polarized current. All the spin transfer phenomena observed in FMs are anticipated in AFMs.
2. Spin-polarized current can induce spin-flop transition, stable precession of AFM vector and parametric downconversion in AFM.
3. Spin-wave spectra of AFM are modified in the presence of spin-polarised current.
4. The values of the threshold currents in AFM should be much lower than in FM due to "exchange amplification".

References

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