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Size dependence of the relaxation rate for non-equilibrium redistributions of the magnetization in Ni–Fe heterestuctures: Exchange vs. relativistic damping scenarios

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ABSTRACT

The relaxation of non-equilibrium redistributions of the magnetization in a model Ni–Fe heterostructure is analyzed on the basis of the Landau–Lifshitz equation with the relaxation terms proposed by Bar'yakhtar. Bar'yakhtar's terms account for both the relativistic (local) and exchange (nonlocal) relaxations. It is demonstrated that the role of the nonlocal relaxation term (a spin current flowing between layers) increases for smaller systems. For nanometer-size systems the nonlocal relaxation term significantly enhances the relaxation of the Ni layer magnetization back to equilibrium. The reason of this size dependence is a competition of fast magnetization dynamics, induced by the nonlocal relaxation term near an interface between metals and slow, relativistic dynamics, which occurs at each point of the Ni–Fe heterostructure. This study provides insight in how to achieve an exceptionally fast remagnetization in magnetic heterostructures after laser excitation.

1. Introduction

Laser-induced non-equilibrium magnetization dynamics in inhomogeneous magnetic materials is currently an area of fundamental and practical importance that is attracting a lot of attention. Several different kinds of inhomogeneous materials have recently been studied.

Laser excitation of thin magnetic films exhibiting a labyrinth-like network of oppositely magnetized domains with structure sizes on the nanometer lengthscale demonstrates the spin transport between differently magnetized regions [1]. This spin transport leads to domain-topography-dependent contribution to magnetization dynamics in the sample.

The excitation of ferrimagnetic GdFeCo alloys with a short laser pulse caused a switching of the magnetization on a picosecond timescale [2,3], something which holds promise for the development of ultrafast magnetic recording. The origin of the switching has been investigated in recent theoretical studies [3–6]. It is important here that GdFeCo alloy displays nanoscale chemical and magnetic inhomogeneities that affect the spin dynamics [7]. In particular, the probe of the optically excited non-equilibrium spin dynamics in GdFeCo on nanometer length scales and femtosecond timescales reveals the Gd spin reversal in Gd-rich nanoregions within the first picosecond driven by the non-local transfer of angular momentum from larger adjacent Fe-rich nanoregions.

Other class of inhomogeneous materials—which is in the focus of the present study—is that of layered metallic heterostructures [8–11] as well as layered magnetic tunnel junctions [12] and synthetic ferrimagnets [13,14]. For these engineered magnetic materials the optical manipulation of the magnetic order is a recent goal [13].

Laser excitation of a Ni–Ru–Fe trilayer system from a Ni side revealed an intriguing magnetization dynamics in Ni and Fe layers: after electron thermalization, the magnetization relaxation back to equilibrium is much faster for an antiparallel alignment of the magnetization of the Ni and Fe layers than for a parallel configuration [8,15]. Strong dependence of the magnetization recovery dynamics on a relative orientation of the magnetization in different layers has recently been observed, too, for magnetic tunnel junctions consisting of two CoFeB layers separated by a thin MgO barrier [12].

In the discussed above experiments an evolution of the modulus of the magnetization vector (a longitudinal evolution of the magnetization) has been observed. Note that the longitudinal evolution of the magnetization cannot be treated on the basis of the Landau–Lifshitz equation [16], with the standard relaxation term (Landau–Lifshitz [16] or Gilbert [17] terms), which describes a transversal magnetization dynamics and consequently preserves the magnetization length.

The difference in magnetization evolution of the two configurations (the parallel or antiparallel alignments) is intriguing as no

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difference would be expected for the magnetization evolution in the two layers treated on the basis of frequently used for a description of the longitudinal evolution of the magnetization the Landau–Lifshitz–Bloch equation [18,19], which is local and the magnetization dynamics proceed independently in the Ni and Fe layers.

The explanation [11] of this unusual dynamics in the Ni–Ru–Fe trilayer has been provided on the basis of the Landau–Lifshitz equation with the relaxation term proposed by Bar'yakhtar [20–22], called also LLBar equations [23]. LLBar equations were derived on the basis of general symmetry arguments and Onsager relations, and employ the concept of both the relativistic (local) and exchange (nonlocal) spin relaxations. Since the general principles used for the derivation of LLBar equations are valid for temperatures both below and above the Curie temperature, it follows that LLBar equations are valid for any temperature, see more detailed discussion in [24]. LLBar equations were used for the description of relaxation of magnetic solitons [25–28], especially Bloch point [28]. LLBar equations give the explanation of the reversal effect in GdFeCo alloys [4,5]. For the Ni–Ru–Fe trilayer the importance of the nonlocal character of the magnetization recovery is established, that is, only the accounting of the nonlocal relaxation could qualitatively explains the experimental observation [11]. As the nonlocal relaxation term conserves the total magnetization of the sample, for the dominating nonlocal relaxation the evolution from initial nonuniform magnetization redistributions is concurrent with the creation of a strong spin current flowing between the layers.

The analysis of the non-equilibrium magnetization evolution in [11] was performed for the concrete experimental parameters of the system, that is, 20% of the magnetization is removed from Ni to Fe and the size of the system is of the order of several nanometers [8].

In this paper we investigate an influence of the nonlocal relaxation term (the spin current flowing between the layers) on the nonlinear relaxation of the Ni layer magnetization back to equilibrium in the Ni–Fe heterostructure for different sizes of the sample and parameters of the initial magnetic redistributions. We demonstrate that the strong spin current from Fe to Ni increases the relaxation rate of the Ni layer magnetization back to equilibrium. For a sufficiently large system size this effect is small and the relaxation of the Ni layer magnetization is determined by the relativistic relaxation. However with a decrease in the system size the relative contribution of the nonlocal relaxation term increases. For a nanometer-size system the evolution of the Ni layer magnetization is driven primarily by the spin current between the layers.

2. Formulation of the problem

Here we briefly state how to model magnetic heterostructures, for details see [11]. For a typical geometry of the experiment with ultrafast dynamics in the Ni–Fe and Ni–Ru–Fe heterostructures a quasi one-dimensional evolution of the magnetization is expected for our problem [8]. For the longitudinal evolution only the length of the magnetization $M = |\vec{M}|$ enters the equations. Adopting the Landau model for the thermodynamic potential LLBar equations take the following form [11]:

$$\frac{\partial m(\xi, t)}{\partial t} = H_{eff}(m(\xi, t)) - \varepsilon \frac{\partial^2}{\partial \xi^2} H_{eff}(m(\xi, t)) \tag{1}$$

where $m(\xi, \tau) = M/M_0$ is a dimensionless magnetization, M_0 is an equilibrium value (temperature-dependent) of the magnetization of a bulk material

$$H_{eff}(m(\xi, t)) = [m_0^2(\xi) - m^2(\xi, t)]m(\xi, t) + \frac{\partial^2 m(\xi, t)}{\partial \xi^2}$$

is an effective magnetic field. The first term on the right-hand side of Eq. (1) describes the relativistic (local) relaxation and the second term corresponds to the exchange (nonlocal) relaxation. Here ξ is a dimensionless coordinate measured in units of $x_0 = \sqrt{2A\chi_{\|}}$, A is an inhomogeneous exchange constant, $\chi_{\|} = dM/dH$ is a longitudinal magnetic susceptibility of a material in the equilibrium state and at zero magnetic field, t is a dimensionless time measured in units of $t_0 = 2\chi_{\|}/\lambda_r$, which is of the order of the time of the longitudinal uniform relaxation of the magnetization (for nickel t_0 is of the order of a few picoseconds [29]). The value of x_0 far from the Curie temperature is of the order of a lattice constant [28,29], but it becomes large in the vicinity of the critical temperature. Note that it is difficult to make formal arguments for the use of the continuous approximation for nonuniform states with the characteristic sizes of the order of a few nanometers. However the using of continuous LLBar equations for a description of the evolution of strongly nonuniform states provides an explanation of the recent experimental observations [11]. Additionally the comparative analysis of discrete and continuous models for magnetic vortices [30] and domain walls [31] in highly anisotropic magnets shows quite good agreement even for the characteristic sizes like 1.5–2 lattice constants. So we believe that the use of continuous approximation is a good approach to the problem and significantly simplifies (compared to the use of discrete models) the analysis.

The quantity $\varepsilon = \lambda_{nl}/\lambda_r$ is the ratio of the nonlocal (exchange) and relativistic relaxation constants. The nonlocal constant λ_{nl} can be determined from the asymptotic behavior for short-wave magnon damping, and then used for a description of highly nonuniform evolution of M. For itinerant-electron ferromagnets, the short-wavelength asymptotics for magnons decrement (called q^2-damping) was recently calculated microscopically [32]. The value of λ_{r} (or, equivalently, Gilbert constant α_G) found, say, from ferromagnetic resonance measurements, can be then used for the analysis of uniform perturbations of M.

We consider the magnetization relaxation in the Ni–Fe heterostructure for two limiting cases: $\varepsilon = 0.1$, where the relativistic relaxation dominates, and $\varepsilon = 200$, where the nonlocal relaxation (the spin current flowing from Fe to Ni) enhances the relaxation of the Ni layer magnetization. Note, again, that only the accounting for the strong nonlocal term ($\varepsilon = 200$) could qualitatively explain the experimental observation [11].

To model the Ni–Fe heterostructure we choose the interface between the metals as the $\xi = 0$ point; the region $\xi < 0$ corresponds to Ni and $\xi > 0$ to Fe. Within the considered model systems of contacted layers of different magnets, the interfaces are considered as very thin, but of finite width, of the order of one atomic size; for the parallel configuration we chose $m_0(\xi) = (5/4) + (1/4)\tanh(\xi)$. This corresponds to the values $m_0 = 1$ inside the nickel layer and $m_0 = 1.5$ inside the iron layer. The value of m is normalized to the equilibrium magnetization of nickel. As our aim is to demonstrate the general features of the evolution we suppose that the values of material parameters are same for the Ni and Fe layers of the system and we present the calculations for the parallel configuration. As the interface between metals is thin, qualitatively, conclusions to an influence of the nonlocal term (spin current) on the relaxation time of the Ni layer magnetization are also valid for the antiparallel configuration.

The laser pulse (with duration of less than 100 fs) has, after electron thermalization (for metals happens approximately within 300 fs), induced a highly nonequilibrium magnetization redistribution $\Delta m(\xi)$. Then the relaxation of $\Delta m(\xi)$ back to equilibrium