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Ballistic transport of spin waves incident from cobalt leads across cobalt–gadolinium alloy nanojunctions

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ABSTRACT

Calculations are presented for the scattering and ballistic transport of spin waves (SW) incident from cobalt leads, on ultrathin ferrimagnetic cobalt–gadolinium $..Co][Co_{(1-c)}Gd_{(c)}]_{\ell}[Co..$ nanojunction systems. The nanojunction $[Co_{(1-c)}Gd_{(c)}]_{\ell}$ itself is a randomly disordered alloy of thickness ℓ hcp lattice planes between matching hcp planes of the Co leads, at known stable concentrations $c \leq 0.5$ for this alloy system. To compute the spin dynamics, and the SW scattering and ballistic transport, this alloy nanojunction is modeled in the virtual crystal approximation (VCA), valid in particular at the length scale of the nanojunction for submicroscopic SW wavelengths. The phase field matching theory (PFMT) is applied to compute the localized and resonant magnons on the nanojunction. These magnons, characteristic of the embedded nanostructure, propagate in its symmetry plane with spin precession amplitudes that decay or match the spin wave states in the semi-infinite leads. The eigenvectors of these magnon modes are calculated for certain cases to illustrate the spin precession configurations on the nanojunction. The VCA-PFMT approach is also used to calculate the reflection and transmission spectra for the spin waves incident from the Co leads on the nanojunction. The results demonstrate resonance assisted maxima for the ballistic SW transmission spectra due to interactions between the incident spin waves and the nanojunction magnon modes. These properties are general for variable nanojunction thicknesses and alloy stable concentrations $c \leq 0.5$. In particular, the positions of the resonance assisted maxima of spin wave transmission can be modified with nanojunction thickness and alloy concentration.

1. Introduction

Recently, layered magnetic nanostructures have drawn considerable attention due to interest in their growing technological potential. Their importance lies in the potential applications of the spin waves of such systems in the so-called magnonics field [1–3], and in spin based nanoelectronics [4–6]. At present the experimental magnonics research work concentrates on the investigation of the properties of spin waves at submicroscopic wavelengths [7]. The objective of the intensive study of spin waves is to determine how to carry and process information coded via their phase or amplitude. The propagation and manipulation of spin waves in magnetic nanomaterials, as multilayers and nanojunctions, and their detection at submicroscopic and nanometric wavelengths remains a key challenge.

The purpose of the present work is to compute the spin waves ballistic transport across magnetic nanojunctions that are relatively insulating compared to known magnetic metallic materials. In this context, there has been considerable efforts to study composite materials based on rare-earth (RE) and transition-metal (TM) elements, as in multilayer systems [8–13], since they present interesting ferrimagnetic properties. The same techniques used to prepare multilayer systems may be equally used to prepare ultrathin alloy nanojunctions with novel but unknown physical properties.

The cobalt–gadolinium alloy nanojunction system between cobalt leads is an interesting example which is explored in the present work. Co and Gd are ferromagnetic materials with Curie temperatures of 120 and 25.2 meV, respectively. It is consequently expected that nanojunctions prepared from cobalt–gadolinium alloys should present very useful magnetic properties at room temperature for device applications.

The study of the properties of *bulk* alloy materials $Co_{(1-c)}Gd_{(c)}$ has been undertaken in the past due to their interesting ferrimagnetism and anticipated potential in device applications, [14,15]. Considerable progress has also been achieved as regard to the properties of the Co/Gd multilayers [9,11,13], where it is observed in these systems that the strong diffusion of Co into the Gd layer occurs leading to ultrathin $Co_{(1-c)}Gd_{(c)}$ alloy interfaces. In recent

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experimental studies [13,11], this diffusion can be controlled experimentally to determine the stable eutectic compositions of the alloy interface, $c \leq 0.5$, preserving the ferrimagnetic character of the multilayers.

Because of the interdiffusion effect, the alloy interfaces in multilayers, at least a few atomic planes thick [9,11], may profoundly influence the properties of such multilayers [8]. This has also been emphasized previously by model calculations which show that ultrathin diffusion alloy interfaces in multilayer systems can significantly modify their magnetic properties [16–18].

The preparation of stable alloy nanojunction systems from Co and Gd, between cobalt leads, is hence technically possible. In an earlier work, we have considered the ferrimagnetically *ordered* alloy nanojunction $..\mathrm{Co}][\mathrm{Co}_{0.5}\mathrm{Gd}_{0.5}]_3[\mathrm{Co}..$ between cobalt leads [19], and presented a model for the spin wave dynamics and ballistic transport at this nanojunction using the Phase Field Matching Theory (PFMT).

The *disordered* ferrimagnetic alloy nanojunction systems $..\mathrm{Co}][\mathrm{Co}_{(1-c)}\mathrm{Gd}_{(c)}]_{\ell}[\mathrm{Co}..$ between cobalt leads, for diverse thicknesses ℓ and concentrations $c \leq 0.5$, have not been studied yet. In the present work, we investigate the scattering and transport properties for spin waves incident from the cobalt leads at these nanojunction systems.

To describe the ballistic scattering and transmission of elementary excitations across embedded nanostructures within the Landauer–Buttiker formalism [20,21], which is a wave problem with multiple incoming and outgoing channels, a detailed analysis is presented using the PFMT method to account for both the propagating and evanescent modes of the system. This method has been successfully developed for the calculation of phonon, magnon, and more recently electron scattering, for a variety of nanostructures and molecular junctions [22,23,19,24–30]. The PFMT method is a theoretical tool which is formally equivalent to the non-equilibrium Green's function method yet transparent and numerically more efficient [19,24–28,30].

The outline of the paper is as follows. The basic elements for spin precession dynamics over a Heisenberg Hamiltonian with nearest neighbor exchange interactions are presented in Section 2. In Section 3, we analyze the problem of the scattering of spin waves at the alloy nanojunction in the virtual crystal approximation (VCA). In particular, the model calculations are applied to compute the reflection and transmission coefficients, and the ballistic SW transport, for SWs incident from the cobalt leads onto the nanojunction systems. We present the numerical results and discussions in Section 4, and the conclusions in Section 5.

2. Theoretical model and Co Lead spin dynamics

Structurally, Fig. 1 illustrates as an example the $..\mathrm{Co}][\mathrm{Co}_{(1-c)}\mathrm{Gd}_{(c)}]_5[\mathrm{Co}..$ nanojunction with five atomic hcp (0001) planes. In general, the choice of $c = 0.1$–0.5 eutectic compositions, which are experimentally textured using present sputtering techniques [13,11], corresponds to stable cobalt–gadolinium $..\mathrm{Co}][\mathrm{Co}_{(1-c)}\ \mathrm{Gd}_{(c)}]_{\ell}[\mathrm{Co}..$ nanojunction alloys for different thicknesses of $\ell = 1$–5 alloy atomic planes.

In these classes of materials, the modifications of magnetic properties of 3d transition-metals as *Co* and 4f rare-earths as Gd have been extensively investigated experimentally, which illuminates the complex interactions of the 3d and 4f electrons. In general, alloying the 3d elements with rare-earth metals weakens the 3d magnetism. The intrinsic magnetic properties can be understood then in terms of the magnetic Heisenberg like exchange interactions between paired spins in the alloy system. The magnetic system of cobalt leads and the nanojunction may then be described by the Heisenberg Hamiltonian [31] with nearest neighbor exchange interactions, as

$$H = -\sum_{p \neq p'} J_{p,p'} S_p . S_{p'} \tag{1}$$

S_p and $S_{p'}$ are spin vector variables on the lattice sites $p \equiv (n, s, m)$ where the integers (n, s, m) count the sites along the x, y and z axes. The Co and Gd spin alignments are assumed ferrimagnetic throughout the system. The exchange in the Heisenberg Hamiltonian is considered between pairs of nearest neighbor spins and the exchange constant $J_{p,p'}$ is ferromagnetic between atoms of the same type and antiferromagnetic between the Co and Gd atoms. In Fig. 1, the irreducible domain for $\ell = 5$ nanojunction is denoted by the hcp (0001) atomic layers $n = -3$ to 3. The pure cobalt leads constitute semi-infinite regions located on either side of the nanojunction for increasing $n \geq 4$ to the right and decreasing $n \leq -4$ to the left.

The 3D ordered spin translation symmetry of the system is broken along the x-axis owing to the embedded nanojunction, whereas the system symmetry is preserved in the hcp (0001) plane. It is then possible to define the normalized dimensionless wave-vectors ϕ_y and ϕ_z, corresponding to wave-vectors k_y and k_z in this plane.

The method employed to study the spin dynamics may be described by the equations of motion for the spin precessions amplitudes [32]. In the present model, dipolar and anisotropy terms, and quantum renormalization for the excitations, are neglected. The system of equation for the spin dynamics for pure semi-infinite cobalt leads of elementary unit hcp cells may be cast in matrix form as

$$[\Omega I - D_B(\zeta, \phi_y, \phi_z)] |U_c\rangle = |0\rangle. \tag{2}$$

$|U_c\rangle = [u_0, v_0]^T$ is the vector of the spin precession amplitudes for the two irreducible sites of the 3D unit hcp cell in the lead bulk. I denotes the unit matrix, and $\Omega = \hbar\omega / J_{CoCo} S_{Co}$ is a dimensionless frequency. This value for the exchange constant between nearest neighbors in bulk hcp Co is determined from the Ising EFT theory [33] which yields theoretical results in good agreement with the

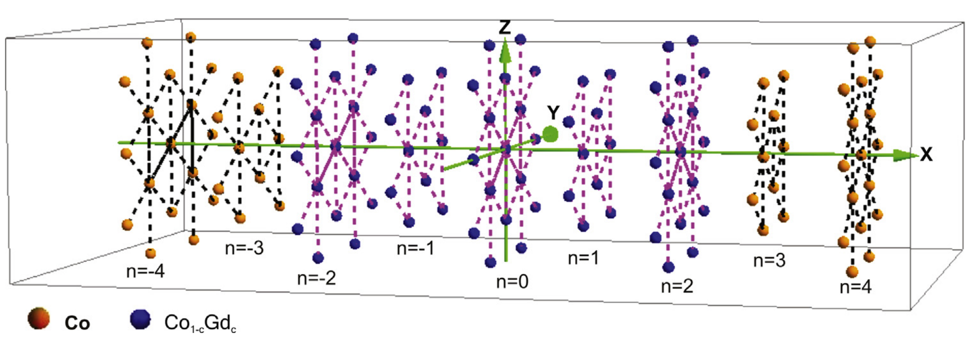

Fig. 1. Schematic representation for a cut of the 3D cobalt–gadolinium alloy nano-junction between crystalline cobalt leads. The hcp crystal c-axis is normal to the hcp (0001) atomic layers. The five layers of the ferrimagnetic alloy $[\mathrm{Co}_{(1-c)}\mathrm{Gd}_{(c)}]_5$ are sandwiched between the two semi-infinite cobalt leads.