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Spin modes and layer magnetization for surface and impurity layer embedded in a ferromagnet

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Abstract

A theoretical study is made for the role of an impurity layer embedded within a semi-infinite ferromagnet in determining the spectra of (0 0 1) surface spin waves and the layer magnetization for the surface and impurity layer. The calculations are described using simultaneously a closed form of the spin-wave Green's function and the matching procedure in the random-phase approximation. Analytic expressions for the Green's functions are also derived in a low-temperature spin-wave approximation. The theoretical approach determines the bulk and evanescent spin fluctuation fields in the two-dimensional plane normal to the surface. The results are used to calculate the energies of localized modes associated with the impurity layer as well as with the surface. Numerical examples of the modes are given and they are found to exhibit various effects due to the interplay between the impurity layer and surface modes. The results derived from the dynamic correlation functions between a pair of spin operators at any two sites are employed to evaluate the spin deviation in the ferromagnet due to the localized modes associated with the surface and with the impurity layer obtained by means of the matching procedure. The correlation functions and the layer magnetization are then illustrated as function of the impurity layer distance from the surface for a given temperature.

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1. Introduction

Interest in magnetic surfaces from both experimental and theoretical points of view has been motivated by the increasing need to acquire knowledge of their associated magnetic, electronic and mechanical properties for high technology applications. The study of surface spin-waves has proved to be very useful, in particular, for determining a magnetic anisotropy constant [1,2] using Brillouin light scattering [3,4], that provides a tool to probe these magnetic excitations, particularly in ultrathin layers and also in dot-structured permalloy layers [5].

It is well known that the localized surface as well as the quantized bulk modes of spin-waves, may occur in an ordered magnetic solid when the magnetic system does not possess full symmetry translation due to a surface or due to the presence of surface imperfections or other lattice defects such as surface reconstruction and/or relaxation in the crystal [6–8]. These imperfections may indeed contribute to a number of physical effects such as changes in the thermal properties and the short lifetimes of spin-waves deduced from their observed large linewidths.

There are many reviews of the properties of surface spin-wave in the case of pure semi-infinite ferro and anti-ferromagnetic systems including their studies by experimental techniques such as light scattering and spin-wave resonance [9,10]. In the same way, it is well known that localized spin-wave states may occur in the presence of an isolated magnetic impurity in bulk Heisenberg magnetic materials at low temperatures [11]. In addition with light scattering technique, the effects may be studied experimentally with neutron scattering. Also, both the defect and resonant modes have been identified. Furthermore, the

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existence of impurities (or other lattice defects) near the crystal surface modify its magnetic surface dynamics properties in two ways: they can give rise to new modes localized in their neighborhood, and they can scatter bulk and surface spin-waves.

A number of theoretical formulations exists for obtaining the relevant surface Green's functions [12], which can give information on magnetic properties at the crystal surface, influence of surface anisotropy on the magnetization as well as thermodynamic stability of surfaces and the modes of their kinetic growth which are also becoming important. The matching method which was one of the calculation procedures used with some success to describe vibrational properties of surfaces and resonances [13], was applied to study the surface spin-waves [14]. In this approach, the eigenvalue matrix is derived from the Heisenberg Hamiltonian and show to contain all information concerning the traveling modes, as well as evanescent modes. The energies of the localized states associated with the surface are also obtained by matching the properties of the quantized bulk modes with evanescent spin-waves occurring on the surface.

Our motivation here is to present some calculations for surface spin-waves with the presence of an impurity layer embedded within a semi-infinite ferromagnet using simultaneously the Green functions formalism and the matching procedure. We consider specifically the case of a single layer of impurity spins implanted in a semi-infinite Heisenberg ferromagnet at a constant distance from the surface. According to the progress of experimental techniques which gives the possibility of fabrication of ultrathin magnetic films, it is possible to create multilayer structures with embedded impurity layers models for that purpose in our theoretical analysis. Among of these structures, we can quote a series of magnetic structures consisting of two Fe films that are exchange coupled through a very thin Cr interlayer [15,16]. We note that the presence of an impurity layer breaks the translational symmetry normal to the surface, so this problem is quite distinct from theoretical studies for a substitional isolated magnetic impurities or a low concentration of random impurities, where a two-dimensional (2D) wave vector is not appropriate for a description of the energy spectrum of the impure system. Let us mention that the impurity atom's spin and exchange will, in general, be different from those of the host atoms. In this context, we assume that the magnetic properties of the system are described by the semi-infinite three-dimensional (3D) Heisenberg spin Hamiltonian considering only the nearest neighbors exchange interactions, and we are interested in understanding how the surface and localized impurity modes affect each other. We shall theoretically treat the standard spin wave approximation in the simplest case of ferromagnetic media magnetized in the z-direction. We first obtain explicit Green's functions for the surface geometry. These results combined with the matching technique formalism are then employed to calculate the localized states of spin-waves associated with the surface and with the impurity layer. In the other hand, the spin correlation functions are also calculated as a function of the position of the impurity spins determined by the impurity layer distance from the surface. These results allow us to deduce the thermal behavior of the magnetization in different layers of the semi-infinite ferromagnet.

The paper is organized as follows: the geometrical model and the theoretical aspects based on the Green's functions formalism are presented in Section 2 in order to derive the quantized bulk modes which allows to build the spin fluctuations field surrounding the surface and impurity layer domain. Also, the spin fluctuation dynamics using Green's functions method are presented for the surface as well as for the impurity layer, with a view to determining unique solutions for the set of propagating modes on a 2D square lattice parallel to the surface. In Section 3, the Green's functions formalism and the matching technique [17] are simultaneously applied to describe the bulk spin fluctuation dynamics as well as the localized spin waves modes associated with the surface and with the impurity layer. The existence, the nature and the shape of these solutions are also discussed in terms of the exchange coupling between spin sites, the values of spin sites and the position of the impurity layer from the surface. Section 4 is devoted to determine the dynamic response of the system in order to evaluate static thermodynamic properties. For this purpose, the calculations of the correlation functions and the magnetization deviation due to localized modes associated with the surface and with the impurity layer obtained from the matching procedure are described for different layers. Numerical examples of the theory followed by the discussion of the results are given in Section 5, whereas the conclusions are summarized in Section 6.

2. Geometry of the model and bulk spin modes

The qualitative features of surface and impurity layer spin waves can be easily illustrated by the model of a semi-infinite ferromagnet with a simple cubic structure. The spin value S occupying the half space $z \leqslant 0$. The condition $z = 0$ depicts the (0 0 1) surface layer with integer $n = 1$. An impurity layer is taken embedded in the ferromagnet at distance Na from the surface (a measures the layer spacing and the integer $N \geqslant 1$). The crystal is assumed to be infinite in the x and y directions and extends from $z = 0$ to $\propto$. The co-ordinates system for the (0 0 1) surface is illustrated in Fig. 1. The z-axis is chosen to be inwardly normal to the surface plane. Layers parallel to the surface are numbered in ascending order, with the surface as the first layer. The integer n is used to label the layers along the z-axis as indicated in Fig. 1. Only the nearest neighbors exchange interactions which are purely quantum mechanical effects that couple neighboring spins favoring their parallel alignment from the bulk to the surface for $T \ll T_c$ (T_c is the Curie temperature) are considered. In other hand, we assume that all spins are ferromagnetically aligned owing to the general character of