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Quantum Confinement Effects on Spin Waves in a Magnetic Multilayer System

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Quantum confinement effects on spin waves at low temperatures have been studied in a FeSi multilayer by proposing a model for the space anisotropy associated to the exchange interaction integral. Spin waves spectrum is calculated for different wave-vectors orientations. Magnetic susceptibility is also obtained in the framework of a Mean Field Theory (MFT). We have found that the bandwidth associated to the magnetic response shows a linear dependence with the interlayer-coupling parameter, in the range of from 0.4, 0.693, 1 with, ranges which correspond to FeSi, Fe and FeAl respectively.

Keywords: Spin waves; FeSi; spin wave frequency; magnetic susceptibility.

Los efectos del confinamiento cuántico en ondas de espín a bajas temperaturas son estudiados in multicapas de FeSi, proponiendo un modelo para la anisotropía espacial asociada a la interacción de la integral de intercambio. El espectro de las ondas de espín es calculado para diferentes orientaciones del vector de onda. La susceptibilidad magnética también es obtenida en el marco de la Teoría de Campo Medio (MFT). Hemos encontrado que el ancho de banda asociado a la respuesta magnética muestra una dependencia lineal con el parámetro de acople Inter-capas, en el rango de desde 0.4, 0.693, 1 con , estos rangos corresponden a sistemas de FeSi, Fe y FeAl.

Descriptores: Ondas de espín; FeSi; frecuencia de onda de espín; susceptibilidad magnética.

PACS: 75.30.Ds; 75.50.Bb; 75.40.Mg; 76.50.+g; 75.40.Gb

1. Introduction

The manipulation of electronic properties in semiconductors allows exploring a new class of components with high-storage capacity and high-flexible non-volatile memory, reprogrammable logic gates and magnetic field sensors with high sensitivity, among others [1]. Magnetic layered systems have a significant role in the development of modern quantum control devices [2–4], and FeSi constitutes an interesting compound widely used in alloys, microchips, transistors, solar cells and a vast variety of electronics. In order to fully understand the effects of metallic or semiconducting doping on Spin Waves properties, it is necessary to get a closer knowledge of the bandwidth symmetry. The model under consideration lies in the framework of the quantum Heisenberg Hamiltonian, the semi classical Landau equation [5] for the magnetic momentum, and linear-order perturbation theory.

This paper is organized as follows: Section II describes the process for obtaining the excitation spin waves frequency and the magnetic susceptibility for a FeSi crystal lattice prototype (FeSi), in the framework of mean field approximation. In Section III we discuss numerical results and Section IV we draw conclusive aspects of this work.

2. Theoretical model

2.1. Spin Wave Frequency

The system in ferromagnetic state (FE) is described by [1]:

$$H = \frac{-1}{2}\sum_{i,j} J_{ij} S_i \cdot S_j, \tag{1}$$

where H corresponds to the Hamiltonian which describes the energy contribution due to the exchange between the ith spin and each one of its neighbor j, the parameter Jij is known as exchange interaction and it depends on the nature of inner electronic distribution [6], and distance between sites. The time-evolution equation for the jth spin-site is obtained for each one of spin states S_j^α, with α = x, y, z, from:

$$\frac{idS_i^\alpha}{dt} = \left[S_j^\alpha, H\right] = S_j^\alpha H - H S_j^\alpha. \tag{2}$$

The right hand side of (2) corresponds to the commutation relationships of the Hamiltonian (1) and spin operators S_j^α. In the low temperature regime, there exists a preferred direction (which can be defined as z) for spin orientations and the mean value is taken as identical for all lattice positions, i.e. $\langle S_i^z \rangle = \langle S_j^z \rangle$. In order to simplify equation (2), we use the rotated wave transformation:

$$S^\pm = S^x \pm i S^y, \tag{3}$$

and introduce the Fourier transformation

$$S_j^+ \to \sum_q S_q^+ \cdot e^{i(qr_i - \omega_q t)}. \tag{4}$$

Then, we solve for S^+:

$$\frac{idS_i^+}{dt} = \left[S_j^+, H\right] = S_j^+ H - H S_j^+. \tag{5}$$

The function $\omega(q)$ (ω_q from now on), represents the associated frequency of excitation modes as a function of the wave vector q, explicitly:

$$\omega_q = \langle S^z \rangle \left[J(0) - J(q)\right], \tag{6}$$

where $J(0) = \sum_i J_{ij}$ corresponds to the average value of the interactions on site j as $q = 0$, while $J(q) = \sum_i J_{ij} e^{iq\cdot(r_i - r_j)}$ represents the Fourier transform for Jij spin wave frequency. For a FeSi-lattice, exchange values are taken as equal for the six-first neighbors of Fe atom in the lattice. In order to introduce the confinement effect, we might consider a different exchange parameter values along the growing axis (z in our case), with two nearest neighbors located at distances a (those in top and below the XY plane), and four-nearest neighbors interacting with exchange parameter $J^{'}$ [7]. Expansion of expression (6) leads to:

$$\frac{\omega_q}{J\langle S^z\rangle} = 2\left[1 - \cos(q_x/2 + q_y/2\right] + 4\xi\left[1 - 1/2(\cos(q_y/2 + q_z r/2)) - 1/2(\cos(q_x/2 + q_z r/2))\right], \quad (7)$$

where $\xi = J'/J$ is the relative exchange ratio, and $r = b/a$ is the indentation relationship along the z axis. Table (I) shows experimental relations between ξ and r [3].

2.2. Magnetic Susceptibility

In order to obtain the expression for the dynamic susceptibility, we add a Zeeman term in Eq. (1). The formalism described for this approach also requires that $|qa| \ll 1$, and restricted to the range of the acoustic modes [8]. The effective magnetic fields acting on S_i, h_i^α is calculated as:

$$h_i^\alpha = -\partial H/\partial S_i^\alpha, \qquad \alpha = x, y, z \quad (8)$$

In the low temperature regime ($T \ll T_C$),T_C being the critical temperature, we introduce the Mean Field Approximation (MFA):

$$S_i^\alpha \equiv \langle S^z\rangle + \mu_i^\alpha e^{-i\omega t}. \quad (9)$$

Here, $\langle S_i^z\rangle$ denotes the spin average eigenvalue at the z direction, and μ_i^α denotes the fluctuating compounds of S_i^α at frequency ω. Under this approach, the quantum nature of S_i^α is still intrinsic in formulae (5), but their fluctuating compounds are not, *i.e*, μ_i^α fields commute. By using the Landau equation for the magnetic torque (10), the amplitudes of the perturbation fields μ_i^α given in (9) are obtained by solving the set:

$$\frac{dS_i^\alpha}{dt} = -i\omega\mu_i e^{-i\omega t}. \quad (10)$$

TABLE I. Relations between ξ y r.

System	ξ	r
FeSi	1	1
Fe	0.693	1.012
FeAl	0.4	1.026

By restricting our solutions only for linear terms in $\langle(S_i^z\rangle)$ and μ_i^α, with:

$$\mu_i^\alpha = \sum_q \mu_q^\alpha e^{-iq\cdot r_i}, \quad (11)$$

the q-space amplitudes ofμ_q^α are finally obtained in matrix form:

$$\begin{pmatrix}\mu_q^x\\ \mu_q^y\end{pmatrix} = \frac{-g\mu_B\left(S^z\right)}{\left(-K_0 + \left(S^z\right)J_q\right)^2 - \omega^2} \begin{pmatrix}-K_0 + \langle S^z\rangle J_q & -i\omega\\ i\omega & -K_0 + \langle S^z\rangle J_q\end{pmatrix}\begin{pmatrix}b_q^x\\ b_q^y\end{pmatrix}, \quad (12)$$

where b_q^x and b_q^y are the external fields applied in directions X and Y, and $K_0 = (\langle S^z\rangle \sum_j J_{ij} - g\mu_B B_0)$. Then, the dynamical magnetic susceptibility reads:

$$\chi = \chi_0\begin{pmatrix}k & i\omega\\ -i\omega & k\end{pmatrix} \quad (13)$$

with $k = (-K_0 + \langle S^z\rangle J_q)(-g\mu_B\langle S^z\rangle)$ and

$$\chi_0 = \frac{g\mu_B B_0}{-\omega^2 + k^2}.$$

The set of equations (7)-(13) describes in a first order approximation both the dispersion relationship and the magnetic susceptibility response for orthorhombic-type Fe-lattices, in particular, under Si/Al doping variations encoded in Eq. (7).

3. Numerical results and discussion

3.1. Spin wave frequency

Spin waves excitations are studied in the range $0 < q_z b < \pi$ in order to observe confinement effects. Figure 1 shows the dispersion laws for three different values of ξ according to Table I. Values of q_Y were given as zero, so we are only studying propagations on q_X, q_Z plane, which might be enough to describe localization effects. Taking $q_X = 0$ as a reference point, we can observe that bandwidths have values of 1.7, 2.8 and 4 (in units of $J\left(S^Z\right)$) for ξ = 0.4, 0.693 and 1 respectively. In the limit of maximum confinement (J'˜ J) the bandwidth is also maximum with larger frequency excitations.

3.2. Magnetic susceptibility

Using Table I, we proceeded to indirectly verify the corresponding theoretical model of magnetic susceptibility, in particular, the variation of the spin-waves bandwidth.

The difference between susceptibility peaks locations represents the size of the bandwidth. Its increment becomes apparent when the confinement decreases and viz. Figure 3 exhibits results confirming the bandwidth calculations of Sec. 3.1.

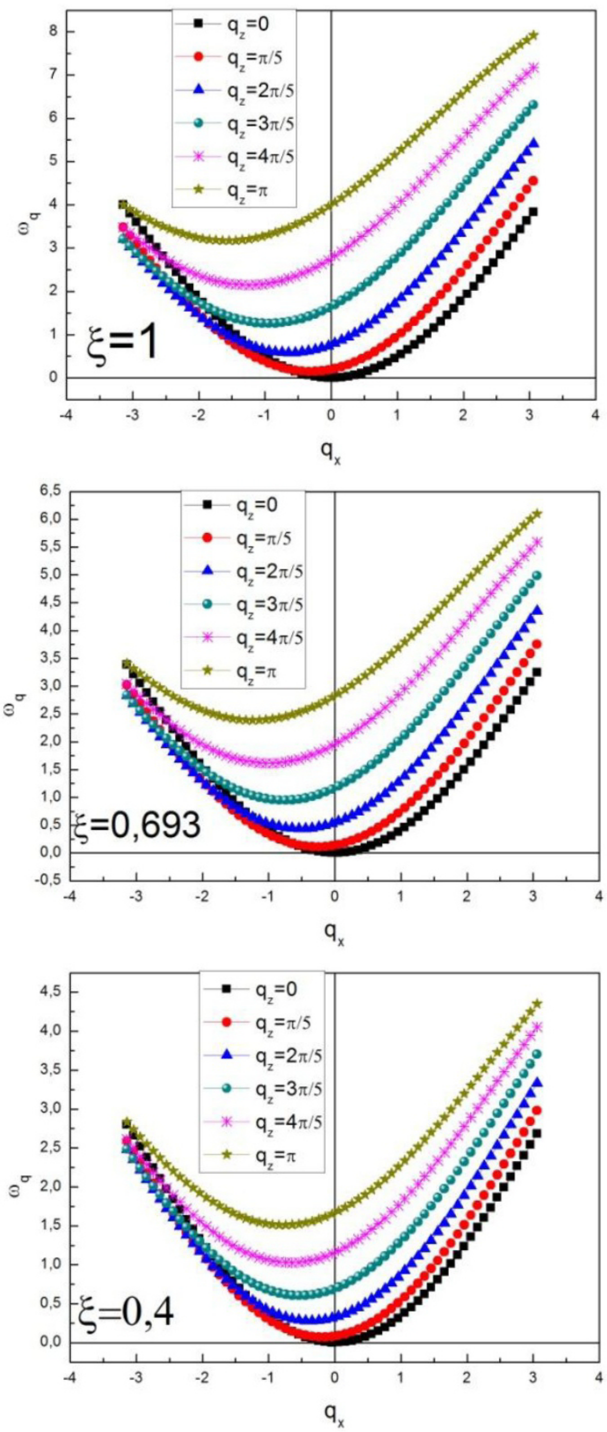

FIGURE 1. Bandwidth for ξ = 1; 0.693 and 0.4 as a function of propagation direction (qx, 0, qz).

A similar calculation allows observing the variation of the susceptibility when a uniform external magnetic field B is applied. This behavior is shown in Fig. 2. It can be noticed the linear dependence between the spin waves bandwidth and the confinement parameter ξ. Also, this figure shows behaviors for FeAl, FeSi and Fe.As shown, the increasing in the applied magnetic field produces a decreasing of the bandwidth, particular effect which is associated to the magnetic confinement of the collective excitations due to the external field.

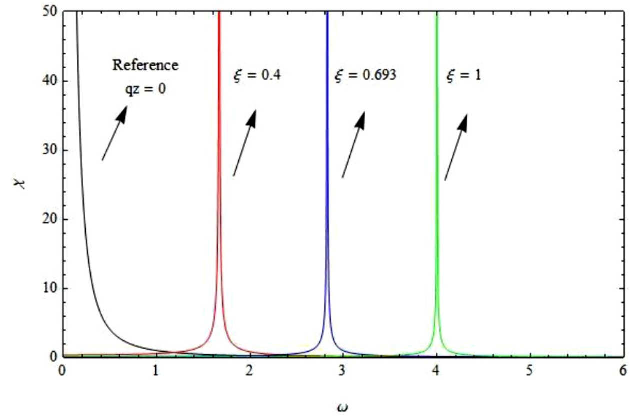

FIGURE 2. Susceptibility values for $q_z = \pi$ and different values of ξ. The susceptibility peaks for each one of the values of ξ matches with the bandwidths found in section 3.1.

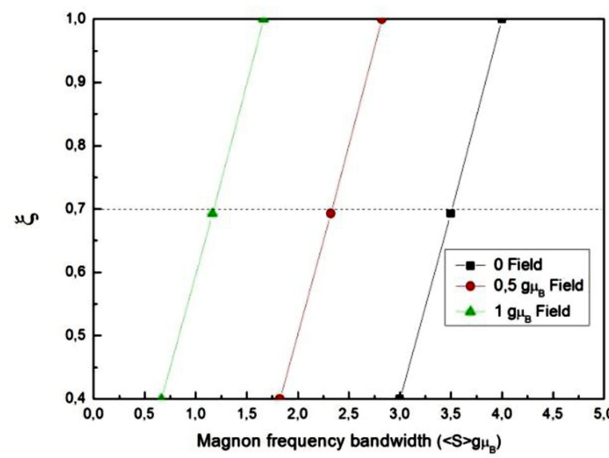

FIGURE 3. Confinement parameter as a function of the magnon Frequency Bandwidth. Values of applied magnetic field for different structures are shown.

4. Conclusions

We calculated the distribution of the spin waves bandwidth (SWBW) in a multilayer system for different directions of the wave vector q. We found that the SWBW increases when the confinement parameter decreases. The dynamic magnetic susceptibility χ for various parameters of confinement was also obtained, indicating that the difference between peaks of susceptibility corroborates the increment at the SWBW when the confinement is smaller. Finally, the SWBW behaves linearly when the applied magnetic field intensity grows.

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1. R. Rodriguez, http://blog.continuum.cl/wp-content/uploads/2008/08/spintronica.pdf, visited in may 02, 2010.
2. S.P. Li *et al.*, *Nature* **415** (2002) 600.
3. M. Tsoi *et al.*, *Nature* **406** (2000) 46.
4. M. Tsoi, *Journal of Applied Physics* **91** (2002) 6801.
5. L.D. Landau and E.M. Lifshitz, *Electrodynamics of Continuous Media* (2nd Ed. BH, 1999).
6. S. Blundell, *Magnetism in Condensed Matter* (Oxford Univ. Press, 2004).
7. L. Dobrzyñski *et al.*, *Solid State Commun.* **46** (1983) 217.
8. M.G. Cottam and D.R. Tilley, *Introduction to surface and superlattice excitations* (Cambridge University press, 1989).