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Surface magnons probed by spin-polarized electron energy loss spectroscopy

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ABSTRACT

Short-wavelength magnons at ferromagnetic surfaces can be probed by electrons. The unique property of electrons, i.e. having a very strong interaction with the surface together with the spin degree of freedom enables one to investigate the spin dependent quasi-particles, e.g. magnons at magnetic surfaces.

We review the experimental results of short-wavelength magnons probed at ferromagnetic Co(0 0 0 1) and Fe(1 1 0) surfaces by spin-polarized electron energy-loss spectroscopy. The differences and similarities to their bulk counterpart are discussed in detail. Although in the case of Co(0 0 0 1) surface magnons behave similar to the ones in bulk Co, in the case of Fe(1 1 0) they possess a smaller exchange stiffness meaning that the effective exchange coupling is smaller at the surface. In both cases, surface magnons have an extremely short lifetime being in the order of a few tens of femtosecond.

1. Introduction

Magnetism at surfaces and in ultrathin films has attracted a lot of attention because of exotic phenomena, which have not been observed in bulk materials [1–4]. Enhanced magnetic moment at the surface [3], perpendicular easy axis [4] and giant magnetoresistance effect [5,6] are all attributed to the presence of the surface and interface. The possibilities of using these new effects observed at the magnetic surfaces and interfaces in magneto-electronic technology have been extensively discussed and even some of the available devices in nowadays technology are based on these properties [7].

Magnetic excitations are well-established subjects in bulk magnetism. They are of crucial importance for understanding the microscopic origins of different observations in magnetism, e.g., the magnetic ordering phenomena at a finite temperature. From a fundamental physics point of view, a complete knowledge of magnetic excitations would lead to a better understanding of the physical phenomena related to the excited state of the system. In the case of low-dimensional magnetic objects or at surfaces, the magnetic excitations should, in principle, reflect the properties of these systems. This knowledge is essential to understand the theory of high-speed response of a magnetic material to different kinds of excitations (for instance high frequency electromagnetic radiations). Moreover, it would allow a prediction of the role and the type of elementary excitations generated within the processes like spin-current induced magnetic switching [8,9]. From the application point of view this information would help us to design magnetic devices, which can be operated at high frequencies.

In a classical description, the wavy-like motions of the atomic magnetic moments, which are caused by the precession of the individual moments are called spin waves. Their representative quasi-particles are referred to as magnons. Long-wavelength (low-energy) excitations are usually treated classically using phenomenological approaches, e.g., using the so-called Landau–Lifshitz–Gilbert (LLG) equation of motion. The dominating magnetic interaction for this class of magnons is the magnetic dipolar interaction [10,11]. Although in various occasions it is shown that the LLG equation fails to describe the magnetic damping mechanisms in ferromagnets [12–15], however, it lies in the central explanation of long-wavelength spin waves, at least where processes like two-magnon scattering are not important. In contrary to this class of magnons the short-wavelength magnons are governed by magnetic exchange interaction and therefore their properties are entirely different than those of long-wavelength magnons.

In this paper we will provide the experimental results of short-wavelength magnon excitations probed by spin-polarized electron energy-loss spectroscopy (SPEELS) on different ferromagnetic surfaces. As examples we discuss the results of Co(0 0 0 1) and Fe(1 1 0) films grown on W(1 1 0) surface. The results of magnon dispersion relation and the lifetime of surface magnons will be discussed.

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Some comparison to the results of the bulk samples probed by inelastic neutron scattering (INS) measurements will be provided. The paper is organized as follows: In Section 2 we introduce the basic concepts needed to follow the paper. In Section 3, the experimental details concerning the sample preparation, characterization, and SPEELS measurements are provided. Section 4 is dedicated to the main experimental results followed by a discussion. A concluding remark is provided in Section 5.

2. Basic concepts

Spin waves governed by exchange interaction may be described by the classical Heisenberg Hamiltonian. In this description the representative quasi-particles of spin waves are referred to as magnons. The simplest form of Heisenberg spin Hamiltonian reads as:

$$H = -\sum_{i \neq j} J_{ij} \vec{S}_i \cdot \vec{S}_j. \tag{1}$$

Here J_{ij} denotes the isotropic exchange interaction between spins $\vec{S}_i$ and $\vec{S}_j$. This Hamiltonian applies to a system of spins, which are coupled via an isotropic exchange interaction in the absence of any external magnetic field and magnetic anisotropy. In the systems with magnetic anisotropy, an additional term, which is proportional to the magnetic anisotropy energy of the system, should be added to Eq. (1). In the presence of the antisymmetric exchange interaction (usually referred to as Dzyaloshinskii–Moriya interaction [16,17]) an additional term, which is proportional to the vector product of the spins ($\vec{S}_i \times \vec{S}_j$) may be added to the spin Hamiltonian [18].

In order to derive the equation of motion, in a semi-classical picture, one may consider the magnetic exchange interaction as the source of a torque acting on each magnetic moment. The equation of motion can be derived as:

$$\hbar \frac{d\vec{S}_i}{dt} = \vec{\tau}_i = 2\sum_j J_{ij} \left(\vec{S}_i \times \vec{S}_j \right). \tag{2}$$

Writing the expansion of the cross product in terms of spin components leads to the following equations:

$$\hbar \frac{dS_i^x}{dt} = 2\sum_j J_{ij} (S_i^y S_j^z - S_j^y S_i^z), \tag{3}$$

$$\hbar \frac{dS_i^y}{dt} = 2\sum_j J_{ij} (S_j^x S_i^z - S_i^x S_j^z). \tag{4}$$

Now if one defines the rising operator as $S^+ = S^x + iS^y$, Eq. (2) can be simplified to:

$$i\hbar \frac{dS_i^+}{dt} = 2S\sum_j J_{ij} \left[S_i^+ - S_j^+ \right], \tag{5}$$

where $S \approx S^z$ denotes the magnitude of spin. By considering a wave form solution for the magnons ($S_i^+ = A_i \exp[i(\vec{q} \cdot \vec{R}_j - \omega t)]$, A_i denotes the amplitude of the magnon with the wave vector $\vec{q}$ and angular frequency of ω at position $\vec{R}_i$) one can simply derive the following expression, which connects the magnons energy (eigen-frequency) to their wave vector:

$$\hbar\omega A_i = 2S \sum J_{ij} \{A_i - A_j \exp[i\vec{q} \cdot (\vec{R}_j - \vec{R}_i)]\}. \tag{6}$$

The above equation is usually used to derive the magnon dispersion relation for any system of interest. We will use it in Section 4 to calculate the dispersion relation of our systems. For an infinitely large crystal with simple cubic structure and considering only the nearest neighbor interaction, the dispersion relation can be written as this simple form:

$$E = \hbar\omega = 2zJS \left[1 - \frac{1}{z} \sum_{\delta} \cos(\vec{q} \cdot \vec{a}) \right], \tag{7}$$

where z is the number of nearest neighbors, $J = J_{ij}$ represents the exchange coupling constant between the neighbors and $\vec{a}$ is the position vector of the respective neighbor. The Heisenberg Hamiltonian provides no information concerning the magnons' damping. The assumption is that the magnons live for an infinitely long time. In reality, the magnons possess a finite lifetime, which for the case of itinerant electron ferromagnets is quite short. We will provide some information on the magnon lifetimes at the Fe(1 1 0) surface in Section 4.2. The classical Heisenberg picture fails to describe the magnon dispersion relation in itinerant electron ferromagnets [19–31]. However, since it provides a simple way of understanding the magnon dispersion relation, we will use it for our data analysis in a comparative way.

In an itinerant ferromagnet the bands are spin-split across the Fermi-level, which can lead to a possibility of single-particle excitations called Stoner excitations. In fact, an electron of majority spin character can jump from an occupied majority band to an empty state in the minority band above the Fermi-level. A hole with majority spin character in the majority band will be left. The electron–hole pairs (Stoner pairs), generated within this process, possess a total spin of $1\hbar$. The energy and momentum of a Stoner pair is given by the momentum and energy difference of the electron and hole in the minority- and majority-band, respectively. The probability of having Stoner excitations depends on the band structure. In two-dimensional metallic ferromagnets, Stoner excitations are spread over the entire Brillouin zone and only a narrow area within the Stoner gap is left. They overlap with the collective excitations. It is shown that Stoner excitations lead to an energy renormalization of the high wave vector magnons, in addition to modifying their damping [28,29,32]. The excitations at very low energies (below the Stoner gap) will not be influenced by the Stoner continuum and may still be described in terms of spin waves.

3. Experimental details

For this study all the experiments were performed under ultra-high vacuum (UHV) condition with a base pressure better than 3×10^{-11} mbar. As with other surface sensitive methods, performing SPEELS experiments in UHV is essential to get rid of the effects induced by adsorbates.

3.1. Sample preparation

The samples were grown in situ in the form of ultrathin films by the molecular beam epitaxy technique. The structure and chemical properties were characterized using low-energy electron diffraction (LEED) and Auger electron spectroscopy (AES). The magnetic properties were studied by magneto-optical Kerr effect (MOKE). The magnon excitations were investigated using SPEELS. In the following section we will briefly introduce our SPEELS spectrometer. We also discuss and describe the basic physical processes involved in SPEELS experiments.

3.2. Spin-polarized electron energy-loss spectroscopy

SPEELS is a spectroscopy technique based on the scattering of spin-polarized electrons from a magnetic surface. In this technique a spin-polarized low-energy electron beam is incident onto the sample surface at a certain scattering geometry and the intensity of the scattered electrons is measured versus their energy loss. As