Brillouin Light Scattering from Multilayers with Noncollinear Spin Configurations

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Brillouin light scattering (BLS) is a well-established technique for the study of layered magnetic systems. Information about the magnetic state and properties of the sample is contained in the frequency position, width, and intensity of the BLS peaks. We have extended our previous ultrathin film approach for the calculation of spin wave frequencies to the calculation of BLS peak intensities. The derived formalism, which allows an easy calculation of BLS intensities even for noncollinear spin configurations, is applied to a Fe/Cr/Fe/Ag/Fe multilayer system. Good agreement with the experimental spectra is found for a wide variety of spin configurations.

In a Brillouin light scattering (BLS) experiment spin waves in a magnetic system are probed via inelastic scattering of photons. The spin wave mode or magnon appears as a peak in the recorded spectrum, which is shifted by the magnon frequency relative to the central elastic peak. The shift reflects either an energy loss or energy gain corresponding to the creation (Stokes condition) or annihilation (anti-Stokes condition) of a magnon, respectively.

Most experiments focus on an analysis of the spin wave frequencies, which contain information about many magnetic properties, e.g. saturation magnetization, anisotropies, and interlayer coupling. With a suitable experimental geometry and procedure, these properties can be determined solely on the basis of the magnon frequencies. The peak width Δ contains information about the spin wave lifetime. However, in many cases Δ is much smaller than the apparatus broadening of about 1 GHz and cannot be resolved. On the other hand, the *scattering intensities*, which are the topic of this work, carry information mainly about the precessional amplitudes of the spin waves, the mode types, the alignment of the magnetic moments, and can even be used to investigate the magneto-optic coupling. Very few publications have yet addressed the issue of the scattering intensities. The detailed information hidden in the peak intensities is of high relevance for many technological applications, such as data storage and communication technology, because the operation frequencies of contemporary magnetic devices approach the GHz regime, where the magnetization dynamics is closely related to the spin wave modes.

Previously [1], we have shown that spin wave frequencies can be conveniently calculated within the ultrathin film approach, treating the intralayer exchange as an effective bilinear interlayer coupling between thin virtual sheets of the ferromagnetic layers. Recently, we have consequently extended this approach to the calculation of the BLS peak intensities [2]. Given the very close relation of the BLS cross-section to the magneto-optic Kerr effect, the depth-resolved longitudinal and polar MOKE coefficients calculated numerically via the usual magneto-optic formalism can be employed in combination with the spin wave precessional amplitudes to calculate full BLS spectra for a given magnetic system. This approach allows an easy calculation of BLS intensities even for noncollinear spin configurations including the exchange modes [2].

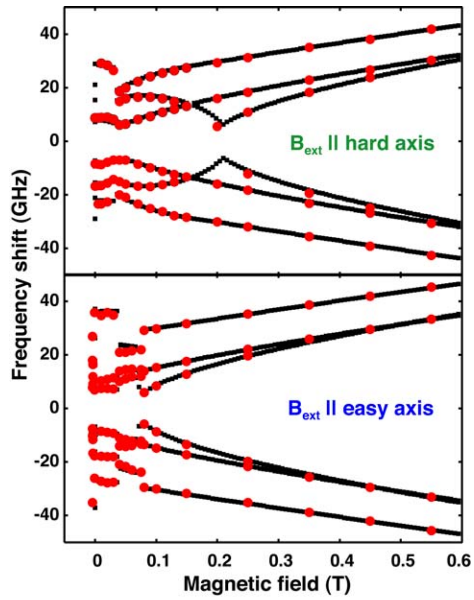

FIG. 1: Field dependence of measured BLS data (red) and least square fit (black) of a Fe(14 nm)/Cr(0.9 nm)/Fe(10 nm)/Au(6 nm)/Fe(2 nm) sample.

Here, we apply the derived formalism to an epitaxial Fe(14 nm)/Cr(0.9 nm)/Fe(10 nm)/Ag(6 nm)/Fe(2 nm) spin valve structure with three ferromagnetic Fe layers. This kind of structures are interesting model systems, which we are also employing to investigate current-induced magnetization switching [3]. Samples have been prepared by molecular beam epitaxy on top of a GaAs/Ag(001) buffer system. The samples have been capped with a 50 nm-thick antireflection ZnS layer. The preparation is described in detail elsewhere [3]. The Cr thickness has been chosen in order to obtain a strong antiferromagnetic coupling in the bottom Fe/Cr/Fe trilayer. The top thin Fe layer is decoupled and can be switched more easily by an external field. As the samples are fully epitaxial and therefore mainly in a magnetic single domain state the remagnetization behavior can be modeled easily. However, as a consequence of the various competing interactions – Zeeman energy, magnetocrystalline anisotropy of all Fe layers, interlayer exchange coupling – a rich variety of different magnetization configurations is possible. The BLS spectra have been recorded using a Sandercock type (2×3) pass tandem Fabry-Pérot interferometer in the 180° backscattering geometry. The external field was applied in the film plane and perpendicular to the magnon wave vector.

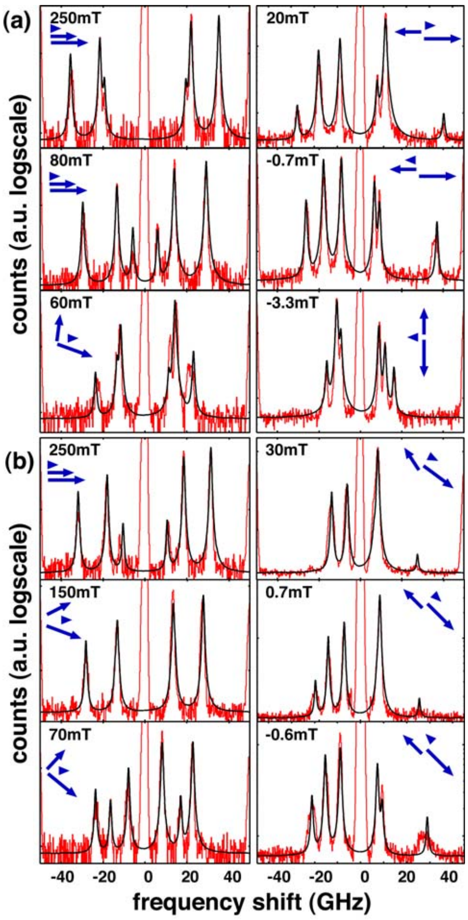

FIG. 2: Experimental (red) and calculated (black) BLS spectra at different fields applied along the easy (a) and hard (b) axis of the magnetocrystalline anisotropy. The computed directions of the magnetic moments of the three Fe layers are indicated with arrows.

Figure 1 shows the experimental spin wave frequencies (red) as a function of the external field applied parallel to the easy [001] (bottom graph) and hard [011] direction (top graph) of the cubic magnetocrystalline anisotropy. Corresponding spectra are shown in Fig. 2. Only the three dipolar modes, which are lowest in frequency, are shown. The graphs can be divided into three distinct field regions bounded by switching events: For low field values ($B_{ext} < 35$ mT) there is a distinct asymmetry between the Stokes and the anti-Stokes side. This unique feature proves an antiparallel alignment of the magnetic moments of the two bottommost Fe layers collinear with the external field applied in easy axis direction [4]. At higher fields ($B_{ext} > 35$ mT) the antiferromagnetically coupled bottom Fe/Cr/Fe double layer switches into a canted configuration with a relative angle between the layers magnetizations of about 90°. The sample saturates at an external field of about 80 and 180 mT in the easy and hard axis configuration, respectively. The hard and easy axis data have been fitted simultaneously in order to extract the magnetic parameters of the Fe layers and the interlayer coupling. For a proper description of the modes all three ferromagnetic layers are divided into 1 nm-thick sheets. This is sufficient to take care of the partial nonuniformity of the modes in the vertical direction. The calculated field dependences using these parameters are plotted as solid lines in Fig. 1. As can be seen, the results of the calculation are in excellent overall agreement with the experimental data.

Experimental spectra for the easy and hard axis configuration are shown as red curves in Fig. 2. Calculated spectra are plotted as black lines. For the intensity calculations we have only used the magnetic parameters extracted from the fit in Fig. 1, and literature values for the indices of refraction of the layers. As the experimental linewidths of all peaks have approximately the same value of about 1 GHz, which is the resolution of the spectrometer, we have assumed a Lorentzian lineshape with this linewidth for the calculation of the spectra. The background level and the absolute intensity have been adjusted manually in order to match the experimental spectra. The surprisingly good overall agreement of both the frequencies as well as the entire spectra proves that the theory well describes the spin wave properties.

In conclusion, our calculation scheme given in Ref. [2] is well suited to gain technologically relevant, quantitative information about spin wave modes, the alignment of the magnetic moments, and the magneto-optic coupling in complex magnetic multilayers.

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