Selected Results

Standing spin wave excitation in antiferromagnetic thin films

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Ferromagnetic and antiferromagnetic systems play important roles in modern information technology ranging from magnetic data storage to sensors. For a functioning device, not only the ground state properties of magnetic devices are of interest. Every time the device is switched, i.e. when a field is sensed or data is written, the magnetic system is excited. The fundamental excitations of magnets are collective excitations of the magnetic moments called spin waves. Established experimental techniques like Brillouin light scattering (BLS) and inelastic neutron scattering (INS) lack the sensitivity for the study of spin waves in individual nanostructures or do not offer high lateral resolution. Here we use the tunneling electrons in scanning tunneling microscopy (STM) to excite standing spin waves in antiferromagnetic thin films. Both the energy and momentum of collective excitations were determined such that the dispersion relation of spin waves perpendicular to the surface in nanoscopic objects can be obtained [1].

The type of sample we investigated is face centered tetragonal (fct) antiferromagnetic Mn thin films grown on Cu₃Au(001) as sketched in the inset of Fig. 1. In bulk magnetic materials, spin waves are free to travel in all three dimensions resulting in a continuous dispersion of the spin wave energy $E$ with the three dimensional momentum $k$. If one restricts one of the dimensions (say the $z$ direction) going to the thin film limit, due to the confining action of the two boundaries (interfaces), spin waves are scattered back and forth between those boundaries. If the film thickness equals the integral multiple of the half wavelength projected along $z$, standing waves are formed. The standing spin waves can be classified by their order $n = 0, 1, 2$, where $n$ reflects the number of nodes in the standing waves along $z$. In agreement with this simple quantization of the spin wave momentum perpendicular to the sample plane, we observe a series of excitation peaks in the inelastic spectra, which are indicated in

Fig. 1: $d^2I/dU^2$ spectra of Mn thin films on Cu₃Au(001) of various thicknesses. The zero order (cross), first order (circle) and second order (diamond) excitation peaks are marked in the figure. These excitations correspond to standing spin waves as sketched in the inset.
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Fig. 1. The measurements were performed on the Mn films in a thickness range from 4 ML to 24 ML on individual nanometer scale Mn terraces. The onset of the inelastic process is characterized by a peak in the $d^2I/dU^2$. Inelastic excitations may occur in forward and backward tunneling direction, leading to peaks in $d^2I/dU^2$ with odd symmetry in $U$ [2]. The zero order excitation corresponds to the energy gap at $k_x = k_y = k_z = 0$, which is the coherent rotation of the magnetic moments of the antiferromagnet. The gap is due to the presence of the magnetic anisotropy interacting with the exchange energy [1]. Besides the peak of the $n = 0$ branch, peaks of higher order can be seen in the spectra. The first order excitation has the wavelength of twice of the film thickness while the wavelength of the second excitation equals the film thickness as shown in the inset of Fig. 1.

From the thickness $t$ of the Mn layer and the order of the peak, we can compute the momentum $k$ using a simple conversion $k_z = n\pi/t$. This way, both the energy $E$ and the momentum $k$ of the spin wave can be obtained from the local excitation spectra. Fig. 2 gives the resulting dispersion deep into the Brillouin zone. At low wave vector, the energy of the spin waves increases linearly as expected for antiferromagnetic spin waves. We obtain a spin wave velocity of $160 \pm 10$ meVÅ by fitting the results with the dispersion relation $E_k^2 = E_g^2 + (v \sin(ka)/a)^2$ of antiferromagnetic spin waves, where $E_k$ is the spin wave energy, $E_g$ is the energy gap, $a$ is the interlayer distance and $v$ is the spin wave velocity. In comparison, we plotted the extrapolated INS data of Ni doped face centered cubic (fcc) Mn along the [001] direction where $v = 185 \pm 12$ meVÅ [3]. The dispersion curve of Ni doped fcc Mn is slightly steeper than our STM results, but in general agrees well with our findings.

We performed ab initio calculations of the spin wave dispersion of fcc bulk Mn. The results of the calculations for fcc and fct Mn are plotted in Fig. 2 together with the experimental results. The fct calculations perfectly agree with the experimental results. As can be seen, the high wave vector spin waves deviate from the linear dispersion. This reflects the proximity to the magnetic zone boundary. The calculated results of fcc Mn have higher energy than fct Mn at the same wave vector.

In summary, we have demonstrated the localized standing spin waves excitation in antiferromagnetic Mn thin films using hot electron injections. The obtained spin wave dispersion agrees well with ab initio calculations and with published INS data on doped bulk fcc Mn. Using tunneling electrons to excite spin waves in STM offers a unique sensitivity and lateral resolution such that the determination of the magnetic excitation spectra of nanoscopic ferromagnetic or antiferromagnetic structures comes within reach.

References

