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Magnon Excitation with Spin-Polarized Scanning Tunneling Microscopy

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Using spin-polarized scanning tunneling microscopy, the local excitation of magnons in Fe and Co has been studied. A large cross section for magnon excitation was found for bulk Fe samples while for thin Co films on Cu(111) the cross section linearly scales with film thickness. Recording inelastic tunneling spectra with Fe coated W tips in a magnetic field, the magnonic nature of the excitation was proven. Magnon excitation could be detected without the use of a separating insulating layer opening up the possibility to directly study magnons in magnetic nanostructures via spin-polarized currents.

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Electron scattering processes are at the heart of modern spin electronics. Besides the strong role of elastic scattering in giant magnetic resistance [1], inelastic processes determine the spin lifetime of polarized electrons in spintronic devices [2], create zero bias anomalies in magnetic tunnel junctions [3], and eventually influence the size of the spin transfer torque in current induced switching of magnetic tunnel junctions [4]. An important elementary process is that hot electrons injected into an electrode of a tunnel junction may scatter there and create magnetic excitations in the form of spin waves. Early experiments on tunneling through an insulating, antiferromagnetic NiO layer showed the possibility of detecting magnon creation in the oxide [5]. Moodera *et al.* later found that similar excitations in the ferromagnetic electrodes of a magnetic tunnel junction are responsible for a reduction of the tunneling magnetoresistance effect at finite bias [3]. Nowadays, a growing number of studies deal with magnetic excitations in planar tunnel junctions [6–8] due to the importance of this effect in current induced switching.

In inelastic tunneling spectroscopy, a physical system is placed in the gap between two tunneling electrodes [9]. When the tunneling electrons have enough kinetic energy eU to excite an inelastic process in the physical system, the tunneling current I is enhanced due to an increase of the number of final states. The onset of scattering creates a step in the differential conductivity dI/dU or a peak in d^2I/dU^2. Inelastic excitation or only virtual excitation may occur, leading to peaks with odd or even symmetry in U [9].

Inelastic scanning tunneling spectroscopy (ISTS) is the method of choice to study excitations with high lateral resolution. It has been successfully used to study vibrational excitations of single molecules [10]. Recently, ISTS has been used to detect spin-flip scattering in Mn atoms and chains [11,12] opening the new and exciting field of magnons in atomic scale nanostructures. It was shown that the cross section for spin scattering needs to be enhanced by placing Mn atoms and chains not directly on a conductive substrate but on an insulating layer to increase interaction.

In this Letter we report on laterally resolved ISTS performed with spin-polarized scanning tunneling microscopy (SP-STM). We show that the cross section for magnon creation in bulk Fe and thin Co films grown on Cu(111) is large enough to allow direct observation without the need of insulating layers and use spin-polarized electrons from a ferromagnetic tip to prove the magnetic origin of the excitation.

All experiments were performed in ultrahigh vacuum ($p < 3 \times 10^{-11}$ mbar). The Cu(111) and Fe(100) single crystals were cleaned by 1.5 kV Ar^+ sputtering and annealing to 720 and 880 K, respectively. The samples were checked with Auger electron spectroscopy which showed no contaminations. Low energy electron diffraction showed sharp spots and a low background indicating a high crystal quality. Co and Fe were deposited by electron beam evaporation from pure (99.999%) material. The rate of deposition was 80 and 40 sec/monolayer, respectively. ISTS experiments were carried out at 4.2 K in a home-built STM which is equipped with three groups of superconducting coils producing fields in arbitrary directions. STM tips were etched in air from W wires and were cleaned in vacuum by flashing such that the very end of the tip was melted.

$I(U)$ and d^2I/dU^2 curves were recorded as a function of position and were averaged, where indicated. The d^2I/dU^2 signal was measured with a lock-in amplifier detecting the second harmonics of a 2–10 mV, 4.2 kHz modulation. The sample bias U was corrected for thermal voltages.

First, to test the tip conditions, we recorded $I(U)$ and d^2I/dU^2 on clean Cu(111) as shown in Fig. 1(a). The $I(U)$ curve is nearly linear, reflecting an Ohmic behavior of the tunnel junction with 2.7 MΩ typical for low voltage $I(U)$ curves. The linear $I(U)$ curve is in agreement with the absence of sharp electronic features in the density of states of Cu(111) near the Fermi level E_F [13]. The d^2I/dU^2 signal is nearly featureless except for some statistical

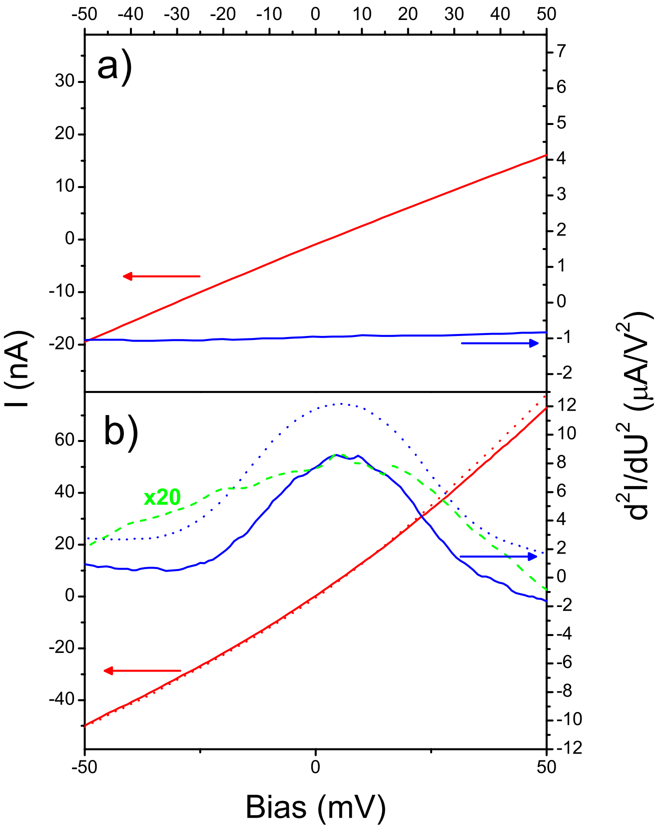

FIG. 1 (color online). $I(U)$ and d^2I/dU^2 curves of (a) Cu(111) and (b) Fe(100) taken with a clean W tip. The modulation amplitude was 5 mV in (a) and 5 mV/2 mV in the dotted and solid curves in (b). The dashed curve was recorded at 77 K with 5 mV modulation and shows thermal broadening. All spectra were averaged over 256 individual curves. While the Cu spectrum shows no peaks, the Fe spectra display a strong peak near the Fermi energy.

noise. No sign of inelastic tunneling was observed. This confirms that the sample and tip were clean. Only tips tested in this way were used in the following experiments.

Second, identical measurements were performed on the Fe(100) surface, which is known to have a surface resonance at 200 mV but no sharp features in the density of states around E_F [14]. In agreement to that, the $I(U)$ curves are nearly linear [cf. Fig. 1(b)]. However, a small deviation is observed around the Fermi level. In accord to this, the d^2I/dU^2 signals have a peak. The peak was fitted by a Gaussian revealing a width of 34.0 ± 0.2 mV with 5 mV modulation and 30.6 ± 0.3 mV with 2 mV modulation and a peak position of 3.6 mV. We checked that this peak is not related to the surface resonance at 200 meV, which itself leads to distinct features in d^2I/dU^2 at higher voltages. The energy resolution Δ of the d^2I/dU^2 signals can be estimated by [10]

$$\Delta = \sqrt{(1.7V_m)^2 + (5.4kT/e)^2}, \qquad (1)$$

where V_m is the modulation voltage and kT/e the thermal energy. At 4 K, this results in a resolution of 8.7 and 3.9 mV for 5 and 2 mV modulation, respectively. The fact that the observed peak widths are much larger illustrates that the widths are intrinsic. In accordance to that, identical measurements carried out at 77 K show a substantial thermal broadening of the peak [dashed curve in Fig. 1(b)]. In summary, this indicates the presence of an inelastic process near E_F. The cross section for the inelastic process was estimated from dI/dU curves (not shown) to be about 27% for tunneling into bulk Fe(100).

The nature of this process can, in principle, be manyfold (e.g., phonons, magnons, or plasmons). The fact that a peak is observed in Fe and not in Cu hints at a magnetic origin. In the following, we will prove this hypothesis.

Plasmon excitation can be readily excluded as the plasmon energy scales as $\hbar\sqrt{\frac{ne^2}{m\epsilon_0}}$, where n is the electron density. The high electron density in metals leads to plasmon energies of the order of eV which are out of range of the observed peak. Spin waves in a ferromagnet show a quadratic dispersion around the Γ-point with a small gap typically below 1 mV due to magnetic anisotropy. While acoustic phonons have similar energies, they show no gap. As our energy resolution is not sufficient to observe a magnon gap, we cannot distinguish phonons and magnons purely by their energy. Magnons, however, carry an angular momentum of $\hbar$. Exciting a magnon is equivalent to removing $\hbar$ of spin moment from the ferromagnet. This implies that creating a magnon by an electron requires that the electron is scattered from minority to majority states.

To verify the magnon nature of the peak we carry out two experiments. First, we show that the cross section of the excitation observed on thin Co films on Cu(111) is proportional to the local Co thickness. Such a behavior is expected for magnons, i.e., it is a necessary condition. For phonons, one would expect that the excitation cross section in Co and Cu are similar, thus leading to a weaker dependence of the cross section on Co thickness. Only in the unphysical case that the phonons are exclusively excited in the Co layer, a linear behavior is expected. Second, we investigate the spin dependence of the excitation.

From spin-polarized electron energy loss spectroscopy (SPEELS) it is known that the excitation probability of magnons in thin Co films is small and of the order of 1:100 when using electrons in the range of 10 eV [15,16]. This is in accord with a spin scattering length of several nm for low energy electrons in ferromagnets [17] and with the absence of a significant spin-flip scattering signal in Mn atoms on Cu(111) [11]. Figure 2(a) shows the topography of ≈3 monolayers (ML) of Co on Cu(111) displaying several open layers. The $I(U)$ and d^2I/dU^2 signal obtained on two different Co terraces corresponding to 3 and 4 ML are depicted in Fig. 2(c) as indicated. The $I(U)$ curves are nearly perfectly linear. Only the 4 ML curve shows a weak bend around E_F. The d^2I/dU^2 spectra recorded on these terraces both show a peak around 13 mV above E_F, while

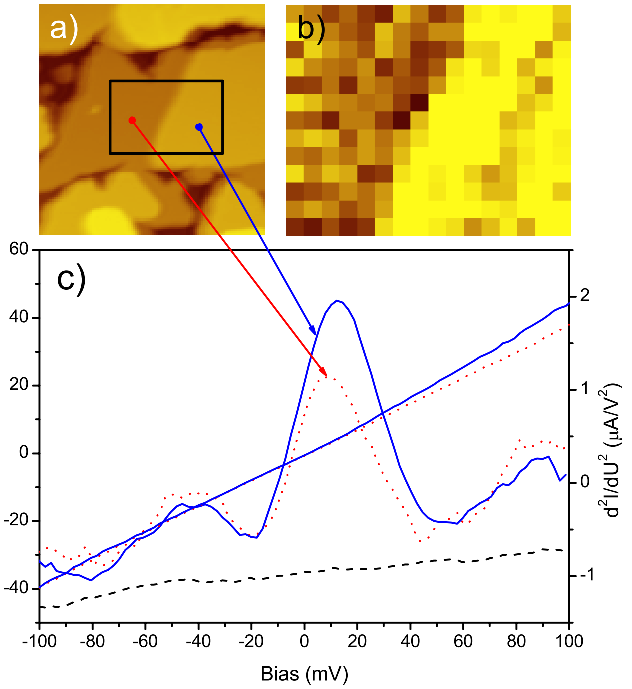

FIG. 2 (color online). (a) Topographic image (40 × 40 nm) of ≈ 3 ML Co on Cu(111). (b) Map of local d^2I/dU^2 signal at 13 mV of the area indicated by the box in (a). (c) $I(U)$ and d^2I/dU^2 curves of Co on Cu(111) as function of coverage taken with a clean W tip. The solid line corresponds to 4 ML, the dotted to 3 ML Co while the dashed represents bare Cu(111) for comparison. The spectra were taken at positions as indicated in (a). The modulation amplitude was 10 mV. The height of the inelastic peak scales linearly with Co film thickness.

the bare Cu(111) spectrum is nearly featureless. Similarly to Fe, we observe inelastic processes, but the peak heights scale with the local Co thickness. The peak ratio is $R = 0.71 \pm 0.1 \approx \frac{3}{4}$. As the spin scattering length in ferromagnets for electrons near E_F is of the order of at least several nm [17,18], a linear increase of magnon excitation probability with film thickness is expected and is in agreement with our observation. Therefore, the first necessary condition for magnon excitation is fulfilled. The cross section for excitation in 4 ML was estimated to about 7% [19]. Saturation effects should only occur at thicknesses comparable to the spin scattering length. Interestingly, SPEELS measurements on thin Co films showed only the excitation of acoustic magnons, i.e., magnons with no node perpendicular to the surface of the film. Higher energy modes with one or more nodes could not be seen [16]. This was explained on the basis of extremely short life times and strong broadening due to coupling of spin waves to the Stoner continuum [21]. In agreement to the SPEELS measurements, we could find no strong peaks at energies associated with the bottom of higher order magnon bands in thin Co films. As STM is a local technique, it may be used to map the inelastic excitations. Figure 2(b) shows the spatially resolved d^2I/dU^2 signal at 13 mV near the step edge separating 3 and 4 ML areas. A higher peak on the 4 ML terrace (right) is reflected by a higher (brighter) signal.

In order to prove the magnetic origin of the excitations and eliminate phononic reasons, we performed ISTS with spin-polarized STM. Instead of bare W tips we used tips coated with 10 ML of Fe. After deposition, the tips were gently annealed by electron heating (200 V, 5 mA) which leads to the formation of Fe clusters several tens of nm thick [22–24]. On planar W(100), these clusters were found to have large coercive fields around 35 mT [24]. While in bare W tips, the spins of the tunneling electrons are equally distributed, magnetic tips are a source of spin-polarized electrons. The direction of spin polarization is fixed to the orientation of the tip magnetization. It is in plane [25], i.e., in the plane of the whisker magnetization and was aligned at 4 K with a magnetic field of +45 mT. As only minority electrons can create magnons in the sample, the relative orientation of the sample and tip magnetizations shall influence the probability of magnon creation.

Spin-polarized d^2I/dU^2 curves on an Fe(100) whisker were recorded as a function of polarity of a field of ±7.5 mT. The field was applied along the easy axis of magnetization, i.e., the [100] direction parallel to the long whisker axis. The coercivity of the Fe whisker was below 7.5 mT as measured *in situ* with the magneto-optic Kerr effect, ensuring full switching of the whisker, while the field is insufficient to switch the tip magnetization. This allows us to toggle between a parallel (or nearly parallel) and an antiparallel (or nearly antiparallel) orientation of tip and sample magnetization. The obtained spectra for Fe-Fe tunneling are presented in Fig. 3. Obviously, the spectra show strong peaks for both tunneling directions, reflecting

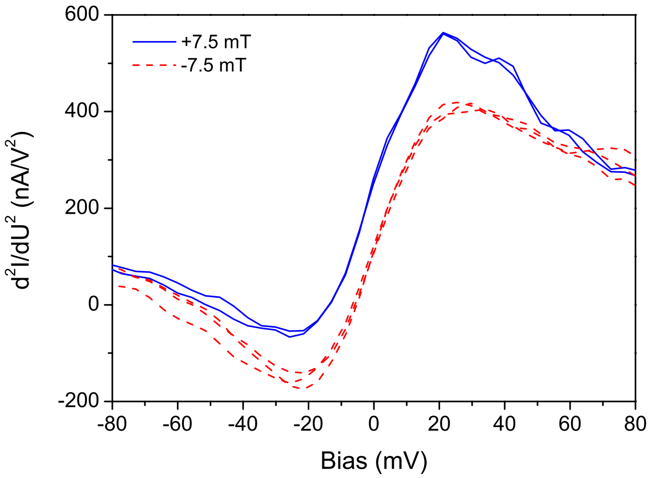

FIG. 3 (color online). d^2I/dU^2 curves of Fe(100) taken with an Fe coated W tip in an applied field of ±7.5 mT showing inelastic peaks ≈ 20 mV above and below E_F. The modulation amplitude was 10 mV. The height of the inelastic peaks vary with the sign of the field indicating a magnetic origin.

excitations in both the tip and the sample. When toggling between the two magnetization states of the whisker, one observes that the height of the peaks depends on the sign of the field, while the total peak-to-peak difference is not changing too much [26]. The magnetic field dependence alone proves that the excitations are of magnetic origin as no other excitation (including phonons) depends on the relative sign of the magnetizations. The details of the spin-polarized excitation can be described by the following model.

The total tunneling conductivity G is given by the sum of the partial conductivities, one for each spin channel. If the magnetizations of tip and sample are parallel (+7.5 mT), $G = G_{\uparrow\uparrow} + G_{\downarrow\downarrow}$, where ↑ denotes a majority state, and ↓ a minority state. Magnons are created only by tunneling minority electrons, so that the magnon creation probability in both tip and sample is related to $G_{\downarrow\downarrow}$. Peaks of identical absolute height are expected in this case (a positive above and a negative below the Fermi energy) [27]. If the magnetizations are antiparallel (−7.5 mT), G is given by $G_{\uparrow\downarrow} + G_{\downarrow\uparrow}$. In this case, the probability for magnon creation in the sample is proportional to $G_{\uparrow\downarrow}$, while in the tip it is proportional to $G_{\downarrow\uparrow}$. In the likely case that the electronic structure of tip and sample are not identical, e.g., due to different crystallographic orientation, the two conductivities are not equal, leading to peaks of different absolute heights. Therefore, if the sample magnetization is switched to antiparallel, it is expected that one of the peaks decreases while the other increases in absolute height in agreement with our observation.

Finally, we focus on the symmetry of the inelastic peaks. The fact that the d^2I/dU^2 spectra of Fe and Co taken with bare W tips show a peak only at positive bias can be due to several facts. Asymmetric inelastic features in the d^2I/dU^2 curves were often found [3,12] and can be related to odd and even components of the differential conductivity due to inelastic or virtual creation of excitations [9]. More importantly, if the excited system is not placed between the two tunneling electrodes but inside of one of the electrodes, the symmetry for the excitation is broken and peaks may appear only in one direction [6]. Our results of strong peaks in the forward direction indicate that magnon excitation is dominated by a hot electron process when tunneling into the ferromagnet and not by a hole annihilation process when tunneling out of the ferromagnet. It is a future task to study the symmetry of the inelastic peak near the Fermi edge with higher resolution and to pinpoint the mechanism of the asymmetry between electrons and holes.

In summary, we have demonstrated that magnetic excitations can be locally detected by ISTS without the use of insulator films. We have estimated a cross section for magnon excitation in bulk Fe of 27% and a cross section of about 2% per ML for the initial monolayers of Co on Cu(111). By combining ISTS with spin-polarized STM, we could prove that the excitations are indeed magnons. In the future, this approach with its high lateral resolution may allow the investigation of laterally confined magnons in nanostructures and the study of the impact of magnon creation on the magnetic configuration.

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[19] The cross section corresponds to a spin averaged mean free path in Co of ≈ 11 nm which disagrees with electron phonon scattering showing mean free paths of the order of μm. If the cross section is, however, due to spin scattering of minority electrons, it corresponds to a mean free path of 5 nm in good agreement with spin scattering lengths at low energies [17,20].
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[26] Lock-in data were carefully compared with a numerically differentiated signal for possible lock-in induced offsets. No offsets were found within the noise level.
[27] There is an unavoidable background on all inelastic d^2I/dU^2 signals due to smooth variations of the density of states.