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Magnetic Hysteresis Loop of Single Co Nano-islands

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Spin-dependent scanning tunneling spectroscopy has been performed on single Co islands on Cu(111) at 7 K in fields of up to 4 T. The differential conductance shows a hysteretic behavior as a function of magnetic field. Symmetric hysteresis curves of the differential conductance are obtained which identify an abrupt switching of the Co island magnetization along the sample normal at fields around 1.5 T, and a reversible change of the spin orientation of the Cr-tip apex with increasing magnetic field. Our result allows a clear-cut assignment of the differential conductance curves in terms of parallel and antiparallel states of the spin orientation between tip and sample. [DOI: 10.1143/JJAP.47.9013]

KEYWORDS: spin dependent scanning tunneling microscopy, scanning tunneling spectroscopy, nanomagnetism, magnetic tunnel junction, nano-islands

Spin-resolved scanning tunneling microscopy (spin-STM) exploits the dependence of the tunnel current and of the differential conductance on the relative spin orientation between tip apex and sample to image spin structures, even with atomic resolution.[1–5] A change of the spin orientation of the tip apex *and/or* that of the sample induces a corresponding change of the tunnel current, which is the basis of the spin contrast.[6] This entanglement between the spin orientation of the sample and tip for the observed magnetic contrast is cumbersome, especially for measurements in field, as it interferes with a clear identification of sample and tip contributions to the spin contrast.

The origin of spin contrast at zero external magnetic field has been ascribed to P and AP states, where P (AP) correspond to the parallel (antiparallel) relative spin orientations between tip and sample.[7–10] However, this assignment neglects the possibility that any two non-equivalent relative spin-orientations of tip and sample give rise to a spin contrast. The individual spin orientation of both electrodes of the system, tip and sample, cannot be deduced at remanence. In previous measurements in an external magnetic field, the contribution of one electrode had been disregarded based on the assumption of a fixed spin orientation of the tip,[7,11] or of the sample.[3,4]

We resolve the contributions of a Cr-covered W-tip and a Co sample to the contrast of spin-STM by measurements during a complete magnetization cycle of Co nano-islands on Cu(111) in magnetic fields of up to 4 T along the sample normal. We observe symmetric differential conductance curves with respect to the magnetic field. This result indicates that both Cr layer and Co island change their spin orientation in response to the applied magnetic field. A sudden switching of the magnetization direction of the Co island induces a hysteretic curve whereas the spin orientation of the tip in a external magnetic field give rise to a continuous and anhysteretic contribution to the differential conductance curve. Our measurements identify at which field values P and AP states are observed, and this opens the way to rigorous spin dependent studies of *single* nanostructures.

Previously, a statistical analysis of magnetic contrast of an assembly of nanostructures has been performed.[12] This procedure gave the average magnetic response over an area of few 10,000 nm^2. Our work offers access to the magnetic switching field of single nano-islands. It opens the way to study the effect of size, shape and structure on magnetic properties of individual nano-objects.

We investigate the magnetic field dependence of the differential conductance of the prototype system Co on Cu(111), where previous studies by spin-STM have revealed an easy magnetization direction of Co along the sample normal.[7,10] The Cu(111) substrate has been cleaned prior to Co deposition by cycles of ion bombardment (Ar^+, 1 keV, 1 μA) and subsequent annealing at 700 K. With deposition of submonolayer quantities of Co at room temperature, triangular double layer high islands with a base length from a few nanometers up to 30 nm are formed[13,14] and subsequently characterized at 7 K by STM and scanning tunneling spectroscopy (STS). STS has been performed by a lock-in technique by applying an AC voltage (10 mV, 5 kHz) to the gap voltage to obtain the differential conductance $dI/dV(V)$.[14] The W-tip (electrochemically etched and subsequently flashed to 2400 K) is covered by Cr to obtain a spin contrast, where the Cr thickness was chosen in dozens of different experimental runs between 20 and 100 ± 10 monolayers (ML).

Figure 1(a) shows the topography of typical Co islands, where we perform $dI/dV(V)$ measurements at the island center to avoid rim effects[15] and the change of the surface state energy with respect to position on the island.[16] Figure 1(b) shows differential conductance measurements at the indicated field values for the islands shown in (a). The main feature of the $dI/dV(V)$ spectra, a peak at −0.3 V, has been reported before for measurement at zero field, and it is ascribed to a localized spin polarized surface state of Co.[7,10,17] Figure 1(b) illustrates the magnetic field dependence of the differential conductance, and sizeable variations of the amplitude and shape of the spectra are found. The amplitude of the field-induced change depends on the gap voltage, e.g., for the peak at −0.3 V we find an increased dI/dV signal at high negative field. Near −0.5 V we observe a decreased conductance at the same field. However, the qualitative change with field and the main features of the signal are similar for all voltages. In the following we will focus on the dI/dV signal at −0.5 V to avoid shifts of the peak reported by Rastei *et al.*[16] In order to link the magnetic field dependence of the differential conductance to the magnetization states of the system, we have recorded $dI/dV(V)$ spectra at different field values during a complete magnetization loop shown in Fig. 2.

We observe a hysteretic behavior of the differential conductance during a cycle of the magnetic field, as indicated in Fig. 2 for islands A and B of Fig. 1. The plot

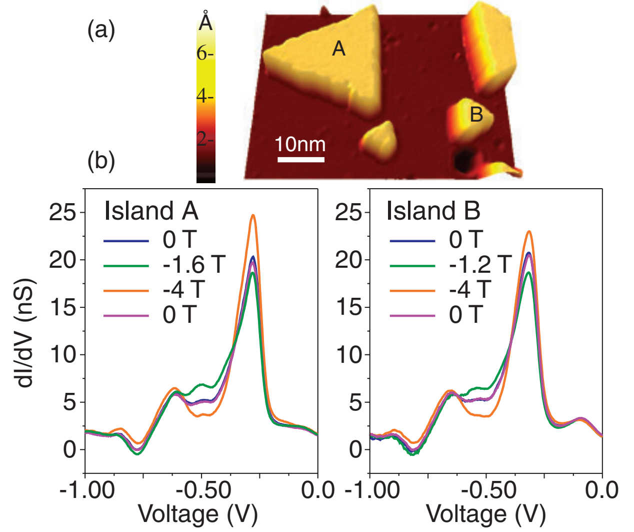

Fig. 1. Top: topographic three-dimensional view of Co islands on Cu(111): island A (size 386 nm^2), island B (46 nm^2). The image is taken at 1 nA and −0.51 V. Bottom: differential conductance $dI/dV(V)$ spectra recorded at the center of island A (left) and island B (right) during a magnetic field scan from 0 to −4 T and from −4 to 0 T. Stabilization parameters: 1 nA and +0.5 V. Electrons tunnel from the sample towards the tip at negative voltage.

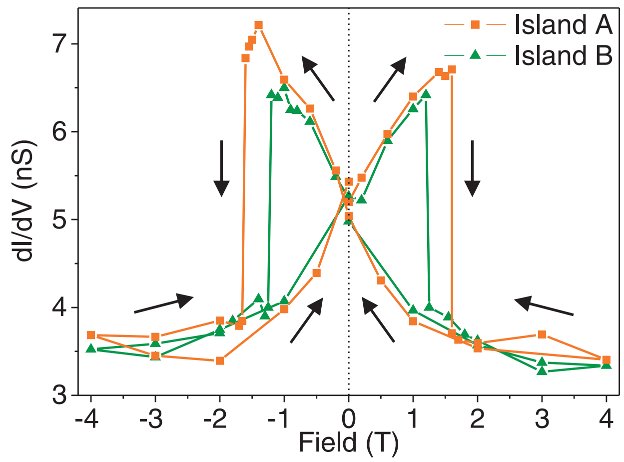

Fig. 2. Differential conductance loops of Co islands A and B of Fig. 1(a) ($V_{gap} = -0.5$ V). The arrows indicate the sequence in which the points are taken. The sharp drop at ±1.625 and ±1.250 T corresponds to the switching of the magnetization direction of the island A and B, respectively. These measurements have been done with a 80 ML Cr coverage on the W tip.

of Fig. 2 shows two remarkable results. Firstly, the plots are symmetric with respect to the field. The plots show a clear hysteresis, e.g., at ±1 T we observed two different values for the differential conductance, depending on the magnetic field history. These plots resemble a shape which is well known from the so-called butterfly curves of tunnel magnetoresistance (TMR) measurements.[18] Secondly, for fields smaller than a critical value, we observe a gradual change of the dI/dV signal with increasing field. At a critical field, the signal changes abruptly. This occurs for island A at ±1.625 T, and at ±1.250 T for island B.

As discussed above, we need to disentangle the contribution from the Co island and the Cr-tip apex from the field dependence of the dI/dV signal shown in Fig. 2. Our measurements shown in Fig. 2 were obtained with the same tip apex. Thus, the differences between the two hysteresis cycles of Fig. 2 can be assigned to island properties (e.g., size, shape, stacking sequence). The sudden drop of the dI/dV signal in Fig. 2 at 1.625 and 1.250 T is therefore ascribed to the magnetization reversal of the Co island along the sample normal. This magnitude of switching field is consistent with previous studies.[7] We conclude that the change of the dI/dV signal, which is similar for both islands for fields smaller than the switching field, is due to the field-induced change of the spin orientation of the Cr-tip apex.

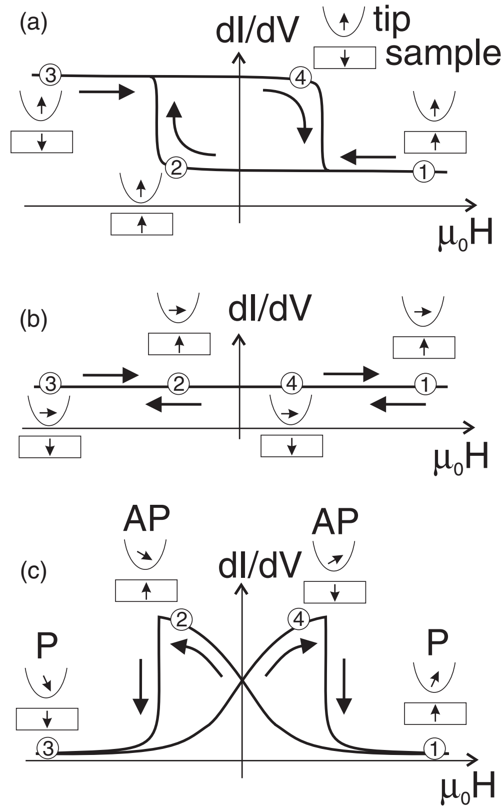

Fig. 3. Sketches of three scenarios for the spin orientation between tip and sample with hypothetical hysteresis loops of the differential conductance during a field loop. The Co island switches abruptly its magnetization direction between 2 and 3, and between 4 and 1. This gives rise to the sharp drop in (a) and (c). Only scenario (c), where the spin orientation at the tip apex changes reflects the experimental result of Fig. 2.

According to refs. 2, 6, and 18, the differential conductance is proportional to $\cos\theta$ where θ is the angle between the orientation of the tip apex spins and the sample magnetization. To attribute a conductance state to a magnetization configuration, P or AP, it is crucial to know the spin orientation of the tip apex. Cr-covered W tips have been used to image magnetic structures with in- and out-of-plane magnetization.[19] One could speculate,[2] based on the antiferromagnetism of bulk Cr, that the spin orientation of the tip apex remains fixed, and that of the Co island could be either parallel or antiparallel to it. Figure 3 illustrates different scenarios for the relative spin orientation between Cr tip apex and Co island with regard to the resulting differential conductance curves. It simply represents schematic views of dI/dV loops based on tip and sample magnetization relative orientation.[6] Three possible cases are sketched, which reflect all relevant scenarios: (a) the spin orientation of the tip is fixed in-plane, (b) fixed out-of-plane, and (c) changes with field.

A fixed spin orientation of the tip along the sample normal leads to an antisymmetric dI/dV hysteresis curve as shown in Fig. 3(a). The conductance states at the positive and the negative end of the field scan should differ due to different relative spin orientation between tip and sample (see arrows in Fig. 3), which is not observed. We rather find in Fig. 2 the same conductance at positive and negative high fields, and this indicates the same relative spin-orientation between Cr tip apex and Co sample. Thus, a fixed out-of-plane spin-orientation of the tip apex is excluded. A fixed spin orientation of the tip apex along the horizontal direction leads to a constant dI/dV curve as shown in Fig. 3(b), which also disagrees with our observation of Fig. 2, and this scenario is therefore also excluded. An intermediate scenario, where the spin orientation of the tip stays canted can also be excluded for the same reasons. Instead, we propose a change of the relative spin orientation between tip and sample in response to an external field as indicated in Fig. 3(c). Scenario (c) gives a symmetric curve, in agreement with our observation. This leads us to the conclusion that the spin-orientation of the Cr-covered W tip apex follows the externally applied magnetic field. Even if the spin orientation of the tip is not completely aligned with the field at high field values, this conclusion remains valid. This effect can be ascribed to a tip which is not atomically flat. In this case, an ideal antiferromagnetic ordering is topologically not possible and uncompensated spins appear which are sensitive to an external field. Scenario (c) with a symmetric hysteresis cycle provides experimental evidence that for our Cr tip an in-plane sensitivity for spin-contrast results at zero field, which was exploited previously.[19] In the range of Cr coverage used (20 to 100 ML), no thickness dependence of the magnetic behavior was found for identical tip preparation. However, scenario (a) might result from a different tip preparation irrespective of the Cr film thickness, possibly with a flat tip apex giving rise to a compensated spin structure and an out-of-plane spin sensitivity.

Our results allow us to conclude that the higher conductance states 2 and 4 in Fig. 3(c) (6.5 and 7 nS in Fig. 2) identify the AP configuration, and that at high field, states 1 and 3 of Fig. 3(c), identify P configurations, as previously assumed.[7,10] Thus, we ascribe the curves in Fig. 1 measured at -4 T to the P state, and the ones measured at -1.6 and -1.2 T to the AP state.

In conclusion, we have performed field-dependent spin-STM on single Co islands. Measurements in high magnetic fields of up to 4 T offer an advanced understanding of the role of the spin orientation of both tip and sample for the observed spin contrast. Our results clearly show that the spin orientation of the Cr-tip apex follows the magnetic field. This study rigorously identifies P and AP states of our tunnel junction, composed of a magnetic tip, the vacuum barrier, and the sample. Thus, spin-STM studies can be analyzed without the need for assumptions on the relative spin orientations between tip and sample. In addition, our method allows to investigate spin dependent transport and switching fields of individual, well characterized nanostructures. This would be difficult to achieve in experiments on planar systems[20] and by averaging techniques.

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