Spin-polarized scanning tunneling microscopy and spectroscopy of ultrathin Fe/Mo(110) films using W/Au/Co tips

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We report on magnetic contrast observed in low-temperature spin-polarized scanning tunneling microscopy (SP-STM) of Fe nanowires deposited on Mo(110) using tungsten tips covered by Au/Co thin films. Due to the spin reorientation transition of Co films on Au an out-of-plane magnetic sensitivity is obtained for tips with thin cobalt films (up to 8 monolayers of Co), while for thicker Co coverages an in-plane magnetization component can be probed. Using W/Au/Co tips with out-of-plane magnetic sensitivity we show that the one (ML) and two (DL) atomic layers thick Fe nanowires prepared using step flow growth on a Mo(110) crystal are perpendicularly magnetized. The reorientation of the tip sensitivity axis has been confirmed by SP-STM measurements of thicker Fe/Mo(110) films, where an in-plane easy axis has been observed for islands thicker than 3 ML. Spin-resolved spectra were measured using the W/Au/Co tips for ML, DL and thicker Fe/Mo films. The spectra reveal strong characteristic peaks at 0.4 eV for ML Fe, and at −0.08 eV and 0.78 eV for DL Fe. Peak positions and intensities depend on the relative orientation of tip and sample magnetization. Spin-resolved spectroscopic data obtained for different tips are compared.

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I. INTRODUCTION

Tip engineering plays a crucial role for spin-resolved scanning tunneling microscopy (SP-STM) and spectroscopy (SP-STS),[1–7] which is the only experimental method enabling imaging of magnetic domain patterns with an ultimate atomic resolution.[8,9] The appropriate tip for the SP-STM experiments should fulfill many requirements. Except for the high spin polarization, the prerequisite of a good tip is a low magnetic stray field, because tips with the large field influence the magnetic state of the sample. Another very important precondition for the SP-STM and SP-STS experiments is the possibility to control the orientation of the sensitivity axis of the tip. This is essential because the magnetic contrast depends on the relative orientation of the magnetization in the tip and in the sample.

Different approaches for mapping magnetization patterns using a STM have been proposed. The modulation technique with oscillating tip magnetization requires different geometries for in-plane and out-of-plane sensitivity.[2,7,10] For SP-STS the variation of differential conductivities dI/dU is exploited and ultrathin magnetic films deposited on the tip surface can be used.[3,6] In-plane and out-of-plane magnetization were measured using different materials evaporated on the tip.[3,6] Even antiferromagnetic films on the tip can be used,[5,6,9] however, the control of the sensitivity axis of the tip, i.e., the magnetization of the tip surface still remains a challenge.

In this paper we report on the magnetic contrast observed by SP-STS using tungsten tips covered by Au/Co thin films. Due to the well-known spin-reorientation transition (SRT) of Co films on Au,[11–15] varying the thickness of the cobalt coating of the tip enables us to probe the direction of the magnetization in the sample. For thin Co coverages ($\leqslant$8 ML) an out-of-plane magnetic sensitivity is achieved, whereas for thicker Co films the in-plane component of the sample magnetization can be probed.

We concentrate our study on the Fe/Mo(110) system because a wide variety of Fe nanostructures can be grown by controlling the substrate temperature, deposition rate, and substrate step density and orientation.[16–18] Moreover, it is expected that the Fe/Mo(110) system should reveal a variety of interesting magnetic properties.[19,20] While the structure and morphology of Fe films prepared on the Mo(110) and W(110) substrates are very similar,[17,18,21,22] magnetic properties of Fe/Mo(110) have been studied to a far lesser extent than Fe/W(110), and qualitative differences have been detected.[19–23] The magnetic easy axis is directed along the [001] direction for Fe/Mo(110),[20,23] while the easy axis is $[1\bar{1}0]$ for Fe/W(110) films. The pseudomorphic ML (ps-ML) Fe/Mo(110) nanostructures are perpendicularly magnetized at low temperatures,[19] whereas the ps-ML Fe/W(110) is magnetized in-plane along the $[1\bar{1}0]$ direction.[22] The double layer (DL) Fe nanowires deposited on a Mo(110) single crystal are perpendicularly magnetized, similarly to the ML Fe nanowires.[24] In this work we exploit the possibility of scanning the same sample area with an out-of-plane and an in-plane sensitivity tip. We observed a spin-reorientation transition between 2 and 3 ML Fe/Mo(110). We have performed spin-resolved spectroscopic studies of the Fe/Mo(110) films using the magnetic sensitive W/Au/Co tips. Spin-resolved spectroscopic data taken with W/Au/Co tips are compared to spectra measured with W and W/Fe tips.

II. EXPERIMENTAL DETAILS

Experiments were performed in an UHV system (pressure $<1\times10^{-10}$ mbar) equipped with an evaporation system for MBE, sample characterization facilities, and a low-temperature scanning tunneling microscope (LT-STM, Omicron NanoTechnology GmbH). The Mo(110) single crystal

was cleaned using the standard procedure,[17–19] including alternating flashing ($T \approx 2200$ K) in an UHV and annealing ($T \approx 1400$ K) in an oxygen atmosphere ($p = 5 \times 10^{-10}$ mbar). The Mo(110) crystal comprises two surfaces: A flat surface with an average terrace width of 200 nm, and a vicinal surface, obtained by a miscut of 1.6° from the (110) crystal plane with steps oriented along the [001] direction and with narrow terraces of 8 nm width. The Fe nanostripes were prepared by step flow growth onto the Mo(110) substrate kept at 700 K.[17–19] The SP-STM and SP-STS measurements were performed at 5 K. We use commercial tungsten tips that were flashed at 2200 K,[6] and subsequently covered by 10 ML thick Au and Co layers at RT. Additionally, for the STS experiments we used clean W tips, and W tips covered by 6 ML thick Fe layers at RT, which reveal in-plane magnetic sensitivity.[6] The STM images were taken in a constant-current mode at a stabilizing current of 1.5 nA. The differential conductance (dI/dU) maps were recorded simultaneously with the topography. The dI/dU signal was measured by a lock-in technique, applying a modulation voltage with a frequency of 7 kHz and an amplitude of 30 mV. The differential conductance maps, where an out-of-plane magnetic contrast has been observed, were measured at a stabilizing bias voltage of 0.3 V; for in-plane contrast, a stabilizing voltage of 0.5 V has been applied. For $dI/dU(U)$ measurements (before feedback was opened) the tip was stabilized at 1 V. The $dI/dU(U)$ spectra, measured from −1 to 1 V of sample bias U (sample voltages with respect to the tip), were averaged over many random positions on equivalent regions.

III. RESULTS AND DISCUSSION

A. Magnetic contrast and spin-reorientation transition in the W/Au/Co tips

Figures 1(a) and 1(b) show the topography of a 0.5 pseudomorphic monolayer (ps-ML) Fe deposited on two different places of the Mo(110) single crystal at 700 K. In Fig. 1(a) very broad (~400 nm) monoatomic Mo(110) terraces are visible, whereas in Fig. 1(b) the average width of Mo terraces is about 100 nm. The ps-ML Fe stripes without islands are formed by step flow on the terraces with smaller widths, because the diffusion length of the Fe atoms is sufficient to reach the edges of the Mo steps at 700 K. On the wider Mo terraces only narrow Fe stripes grow at the step edges and Fe islands nucleate on the terrace. The location of the Fe atoms on the Mo(110) surface is much more visible on the dI/dU maps presented in Figs. 1(c) and 1(d). They were simultaneously measured with the images in Figs. 1(a) and 1(b), respectively. The element specific contrast, resulting from the differences of the dI/dU signal, depends on the local electronic surface properties that are different for Fe and Mo. The element specific contrast enables us to propose a topographical model of the Fe nanostructures on the Mo(110) surface, as illustrated in Figs. 1(e) and 1(f).

The Fe islands and Fe nanowires show two different colors, representing two different values of the local dI/dU signal for equivalent surface regions [ML Fe/Mo(110)] [Figs. 1(c) and 1(d)], though the spin-averaged conductance signals of the ML thick Fe nanostructures are the same, as can be concluded from the STM measurement performed with clean tungsten tips (not shown here). STM images and conductivity maps shown in Fig. 1 were measured using W tips covered by 10 ML Au, and by 4 ML Co. It is known from the literature[13] that 4 ML Co prepared on W(110)/Au reveal an out-of-plane magnetic easy axis. Therefore, one may expect that the magnetization of the tip is oriented perpendicular to the front plane of the tip, i.e., along the tip axis, leading to an out-of-plane magnetic sensitivity of the tip at low temperatures.[14] Obviously, the contrast observed for the Fe nanostructures is of a magnetic origin. Indeed, it has been shown recently, using SP-STM with Cr-coated W tips, that the ps-ML Fe on Mo(110) is perpendicularly magnetized at low temperatures.[19] Variations of the conductance signal observed for the Fe nanostructures are caused by spin-

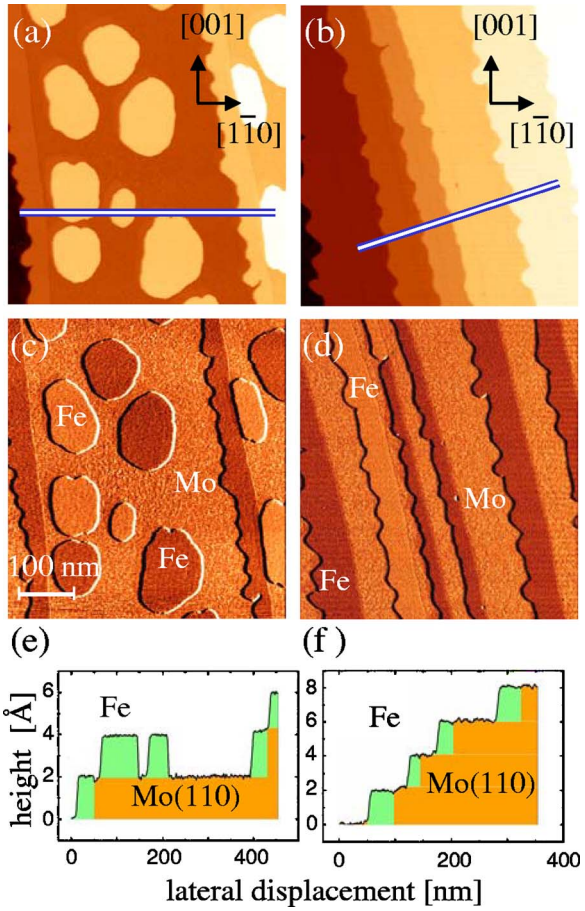

FIG. 1. (Color online) STM images (500×500 nm^2) of 0.5 ps ML Fe grown on Mo(110) at 700 K, measured at two different places on the substrate with broad (~400 nm) monoatomic terraces (a), and (b) with 100 nm terraces. (c) and (d) Differential conductance (dI/dU) maps, measured simultaneously with the topographic images (a) and (b), respectively. Images and conductance maps were measured using the W/10 ML Au/4 ML Co magnetic tip. The Fe nanostructures reveal an out-of-plane magnetic contrast. (e) and (f) Topographic model of the Fe nanostructures on the Mo(110) surface using line scans taken from the STM images (a) and (b), respectively.

dependent vacuum tunneling between the magnetic W/Au/4 ML Co tip and magnetic Fe nanostructures. The W/Au/4 ML Co tips reveal out-of-plane magnetic sensitivity. It turns out that the W/10 ML Au tips covered by thicker Co films (up to 8 ML) reveal an out-of-plane sensitivity as well, in contrast to the spin reorientation transition near 4 ML, as observed for ultrathin films at room temperature.[11–13] The lower temperature in our case might be the reason for the shift of the SRT to higher thicknesses.[14]

DL Fe nanowires can be prepared on the Mo-stepped surface in a similar way as the ML Fe nanowires.[17,18] In this case, one obtains an array of alternating ML and DL Fe nanostripes. Using the tip with the out-of-plane magnetic sensitivity, we found that the DL areas are perpendicularly magnetized, too. This can be concluded from the observation of an alternating contrast in adjacent DL stripes, as illustrated below, indicating a strong dipolar antiparallel coupling between adjacent DL nanowires, as in the case of Fe on W(110).[21,28]

Figures 2(a) and 2(c) show the topography and corresponding conductance map of 1.5 ML Fe deposited on Mo(110) at 700 K, measured using a W/Au/16 ML Co tip. The sample surface reveals monoatomic Fe steps. Areas of ML and DL coverage are easily distinguished on the dI/dU map [Fig. 2(c)], because DL and ML have a different electronic structure. There is no dI/dU contrast between areas where the Fe has the same thickness. This indicates that the tip is in-plane magnetized (the ML and DL Fe nanostripes were perpendicularly magnetized) or that the tip reveals no magnetic sensitivity at all. The lack of the contrast could also be due to an uniform magnetization, however, from our previous study[24] [see also Fig. 2(e)] we know that adjacent DL nanostripes are magnetized in opposite directions because of the dipolar coupling. Information on the magnetic contrast can only be gained if a different dI/dU value is observed for areas with the same spin-averaged electronic structure, i.e., in our case, for areas of the same thickness.

With an increase of the Co thickness, the W/Au/Co system will approach the critical thickness for the spin reorientation transition of the Co coverage. This will weaken the Co anisotropy,[15] which in consequence will cause changes of the tip magnetization orientation due to interactions with the sample stray fields during the scanning. The interaction causes a sudden reversal of the contrast and can be easily detected, as illustrated in Fig. 3.

In order to prove the in-plane sensitivity of the W/Au/16 ML Co tips for which we expect an in-plane magnetization at the tip apex,[11–14] we deposited 2 ML Fe on Mo(110) at 750 K. The Fe film morphology changes for higher coverages, when Fe is deposited at elevated temperatures on the Mo(110) substrate.[17,18] The Fe film forms well-separated, 3–6 ML thick Fe islands, as demonstrated in Fig. 2(b). When the thickness of Fe is increased, the magnetic shape anisotropy becomes stronger than the magnetic interface anisotropy, and an in-plane orientation of the magnetization is favored. On the islands we observe a dI/dU contrast: Dark and bright Fe islands can be distinguished in the dI/dU map shown in Fig. 2(d). As shown above [Fig. 2(c)], the W/Au/16 ML Co tips reveal no out-of-plane magnetic sensitivity. Moreover, the observed contrast cannot be induced

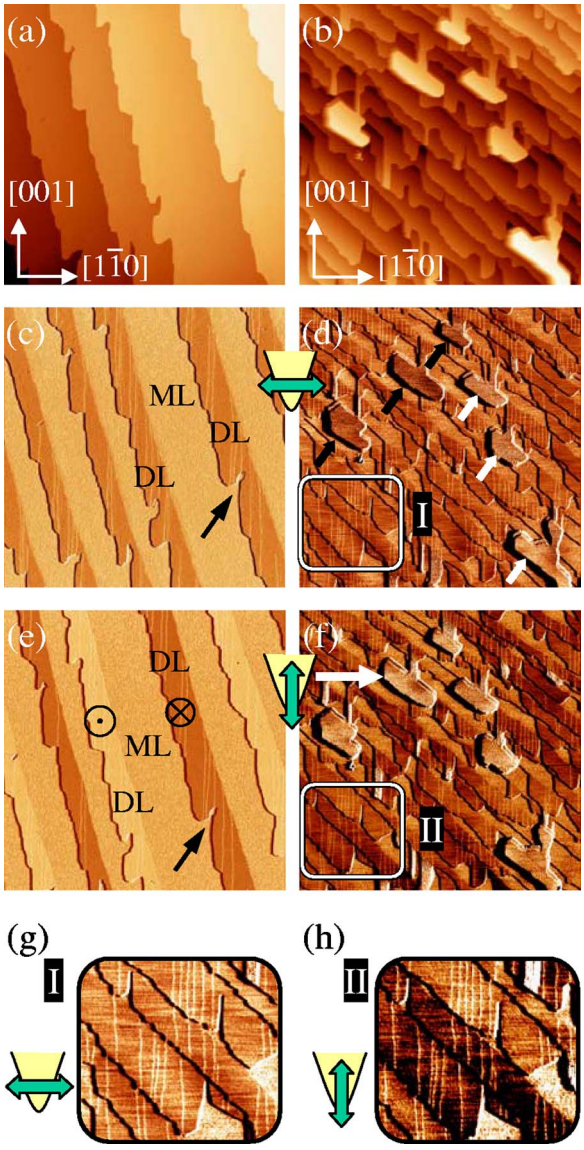

FIG. 2. (Color online) (a) and (b) Topographic STM images (500×500 nm^2) of 1.5 and 2 ML Fe grown on Mo(110) at elevated temperatures, respectively. (c) and (d) dI/dU maps measured using W/10 ML Au/16 ML Co tips simultaneously with the topographic images (a) and (b), respectively. Fe islands indicated by arrows in (d) reveal an in-plane magnetic contrast. (e) and (f) dI/dU maps measured using tips with diminished Co thickness after the application of voltage (10 V) pulses and taken at the same sample area as in (c) and (d). The scan area in (e) is slightly shifted with respect to (c), note the marks. (g) and (h) are enlarged areas I and II of the (d) and (f) dI/dU maps, respectively. Note that out-of-plane magnetic contrast for the DL Fe nanostripes is clearly visible only in (h). The orientations of the magnetic sensitivity axis of the tip are schematically shown for each conductivity map. The large white arrow in (f) denotes the island, which intensely reveals an inhomogeneous magnetization.

by the stray field of the tip interacting with the magnetized islands, because this interaction always tends to minimize the contrast. Thus, we conclude that we observe an in-plane magnetization component on thicker Fe islands. The easy axis appears to be along the in-plane [001] direction, as

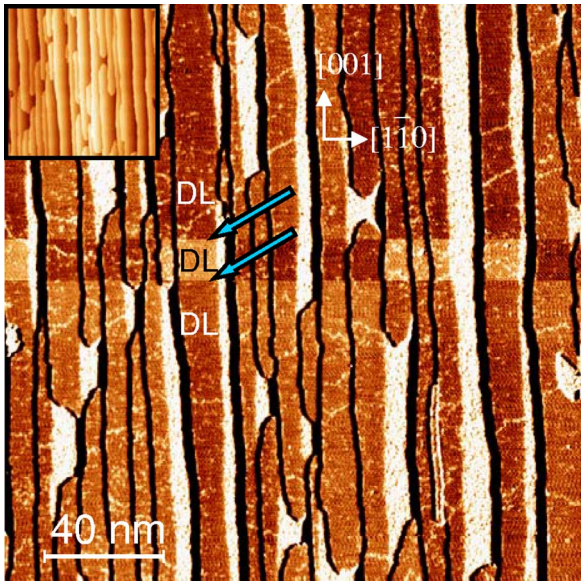

FIG. 3. (Color online) The dI/dU map (500×500 nm^2) measured for 1.5 ML Fe grown on the vicinal Mo(110) surface. The insert (upper left corner) shows simultaneously measured topography of the sample surface. Both images have been measured using W/10 ML Au/9 ML Co tip. While the topographic image shows no irregularities, the dI/dU signal is reversed for the same DL Fe nanowire, as denoted by arrows. Note that after the switching event magnetic contrast has changed, indicating canted magnetization of the tip when critical thickness for the spin reorientation transition of the Co coverage is achieved.

shown in Ref. 20. Not only the 4–6 ML thick islands, but also the narrow 3 ML thick bridges, show this contrast, indicating in-plane magnetization for Fe areas thicker than 2 ML. From Fig. 2(d) alone, we cannot exclude that the magnetization in the Fe islands has an out-of-plane component, too. But the fact that the tip is sensitive to in-plane magnetization is evident.

The application of electrical field pulses (10 V) to the in-plane sensitive tip with thicker Co coverage causes a transfer of magnetic material from the tip to the sample. This diminishes the thickness of the Co coverage. Assuming that in our experiments a distance between the tip and sample amounts to 10 Å[25,26] we obtain an amplitude of the electric field of 1 V/Å, for which one can expect field evaporation of Co atoms.[27] After the application of electric field pulses, the tip is moved back to the area scanned before. Now, we observe different dI/dU signals on DL areas [Fig. 2(e)], as in the case of using W/Au/4 ML Co tips. The contrast is caused by a tip with perpendicular magnetic sensitivity. Similar voltage pulses were applied after scanning, Figs. 2(b) and 2(d). Then, Fig. 2(f) reveals different dI/dU values on DL areas. The difference is emphasized in the enlarged lower left parts (region I and region II) of Figs. 2(d) and 2(f) presented in Figs. 2(g) and 2(h), respectively. The DL Fe areas in Fig. 2(g) reveal a homogeneous dI/dU signal, whereas in Fig. 2(h) strong differences are observed. This observation confirms that the tip has out-of-plane sensitivity after the application of field pulses. The previously observed contrast on the thicker Fe islands has vanished, indicating that here the magnetization has almost no out-of-plane component left, except maybe on the second left island, indicated by the white arrow in Fig. 2(f). This small remaining contrast might be attributed to an inhomogeneous magnetization orientation. The existence of the inhomogeneous magnetization in this island may be explained if we assume that except for a large in-plane magnetization component there is a small out-of-plane component, which is reducing the magnetic stray field of the island, and changes its orientation for a different island area. The up (bright) and down (dark) magnetized DL Fe areas in Fig. 2(f) form a stripelike superstructure of two up- and three down-magnetized stripes running from the upper left to the lower right corner of the image. The period of this stripelike structure is 250 nm. It is not aligned with the Mo steps. This might be an indication of a stripe domain pattern.[29]

Obviously, the application of voltage pulses for the reduction of the Co thickness is a hard to control process, but surprisingly we quote a success rate of 50%.

TABLE I. Composition and magnetic characteristics of the tips used for the spectroscopic measurements.

Index	Tip	Magnetic sensitivity
A	W	—
B	W/10 ML Au/4 ML Co	Out of plane
B′	W/10 ML Au/8 ML Co	Out of plane
C	W/10 ML Au/16 ML Co	In plane
D	W/6 ML Fe	In plane[a]

[a]See Ref. 6.

B. Spectroscopy

In the following we discuss the spectroscopic results for the ultrathin Fe/Mo(110) films. First, we present the measurements that have been performed for two kinds of samples: for a 0.5 ML Fe/Mo(110) sample (sample I), i.e., for ML Fe nanostripes grown at the steps of the Mo substrate, and for a 1.5 ML Fe/Mo(110) sample (sample II), where the Mo substrate is covered by an array of alternating ML and DL Fe nanostripes. In our measurements we have used different tips, which are described in Table I. Spectra taken with the tungsten and the W/6 ML Fe tips can be compared with previously reported spectra for Fe on W(110).[6] The spectra are presented in Fig. 4. We focus our studies on the range of positive voltages, i.e., for $-0.2\ \mathrm{V}<U<1\ \mathrm{V}$, where the unoccupied states of the sample are probed by the occupied tip states, which as a first approximation[30] should be independent on the tip material. For negative energies, the spectra are influenced by tip-induced states and they may strongly differ for different tips. Moreover, the usage of different tips allows to distinguish sample-induced features in the spectra from tip-induced peaks that may occur for the positive voltages, too.

Figure 4(a) shows $dI/dU(U)$ spectra for a clean Mo(110) surface obtained by a tungsten tip (tip A). Except for the small peak at −0.015 V, which is very likely due to a W

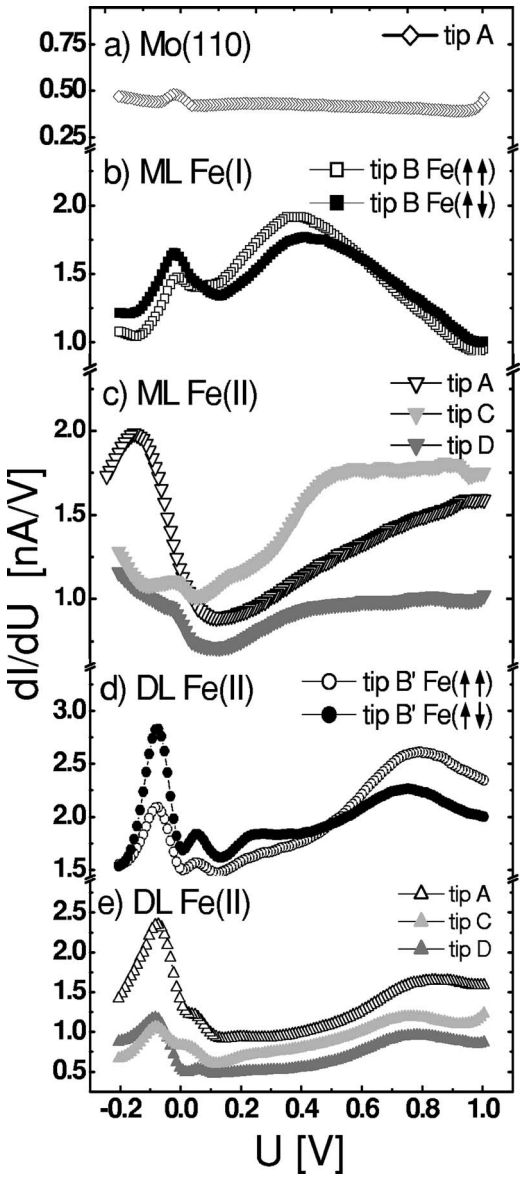

FIG. 4. The dI/dU spectra measured for a bare Mo(110) surface (a), for the ML Fe nanostructures (b) and (c), and for the DL Fe nanowires (d) and (e), respectively. Presented spectra were obtained for two samples: for 0.5 ML Fe/Mo(110) (sample I), and for 1.5 ML Fe/Mo(110) (sample II), and they have been measured using different tips, which are described in Table I.

tip-induced state, no peaks have been observed. Similar results have been obtained using other tips (see Table I). Interestingly, similar featureless spectra have been measured for W(110).[26,31] This experimental observation can be assigned to the similarities of the 4*d* (Mo) and 5*d* (W) band structures of the bcc(110) surface.

The spin-resolved spectra measured for the ML Fe nanostructures from Fig. 1 reveal predominant features at $U=+0.38$ V and $U=+0.42$ V [Fig. 4(b)]. These spectra have been measured using the magnetic W/Au/Co tip (tip B) with an out-of-plane magnetic sensitivity. Depending on the direction of the magnetization of the ML Fe nanostructures, the peak for "up" orientation is shifted relative to the position of the peak for "down" orientation by 0.05 V. Note that we do not know the absolute and relative magnetization orientation. Tentatively we assign parallel orientation to the spectra that have a larger dI/dU value at the voltages used to measure the maps shown in Figs. 1 and 2 in agreement with Jullière's model,[32] i.e., parallel orientation of the tip and sample magnetization is attributed to the "bright" Fe regions whereas "dark" Fe regions are assigned to antiparallel orientation. Additionally to the shift of the peaks, we observe a difference in the peak intensities, too. Both observations can be expected because theoretical predictions[33] reveal different densities of states for minority and majority bands for 1 ML Fe on Mo(110) or on W(110). The change of the intensity of the peaks, which is observed when changing the magnetization orientation in the sample,[34,35] can be explained in the frame of the Jullière's model.[32] Switching between parallel and antiparallel orientation of the tip and sample magnetization actually causes that during spectroscopic measurements we probe a dissimilar density of states, i.e., once we probe majority, and once minority band states that are different due to the exchange splitting. However, the large shift of the peaks (50 mV) for spectra with a different magnetization direction can be understood if we assume that the observed broad peak is a sum of two adjacent peaks that change intensities when changing the relative magnetization orientation. The variation of their relative intensity appear as a shift in the sum signal because the individual peaks are not resolved in our spectra. This behavior might indicate an exchange split surface state. A characteristic peak for the ML Fe/W(110) system at about 0.4 eV has also been observed in low-temperature spin-resolved spectra, which were measured using in-plane (W/Fe) and out-of-plane (W/Gd) sensitive tips.[34,35] The existence of this peak seems to be temperature independent because it also shows up in spectra recorded at room temperature.[31]

We have measured spectra for the ML Fe region in the 1.5 ML Fe/Mo(110) sample (sample II), using tips described in Table I [see Fig. 4(c)]. Surprisingly, spectra obtained for sample II differ from the ML Fe spectra presented in Fig. 4(b) (sample I). However, spectra taken with the same tip were reproducible for both samples I and II. The pronounced peaks shown in Fig. 4(b) are smeared out and shifted toward higher energies, although the electronic structure of the ML Fe should be the same for samples I and II. The observed differences cannot be attributed to tip effects because the observed peaks are induced by the sample and, as we will show below, the DL Fe sample states are nicely reproducible, independent of the tip material. Instead, the changes of the electronic structure of the ML Fe can be attributed to the presence of adsorbates, which can easily modify the electronic structure of the substrate. It is known that due to the large strain, especially the first ML Fe on Mo(110) is very reactive,[36–38] and easily adsorbs rest gas molecules. Therefore, although prepared in UHV conditions, the electronic structure of the ML Fe may differ from experiment to experiment.

Figure 4(d) shows spin-resolved spectra for DL Fe stripes taken with out-of-plane sensitive W/Au/Co tips for sample II. They reveal two prominent peaks at −0.08 and 0.78 V, and two smaller peaks at 0.06 and 0.2 V. Depending on the relative magnetization orientation of the DL Fe stripes and

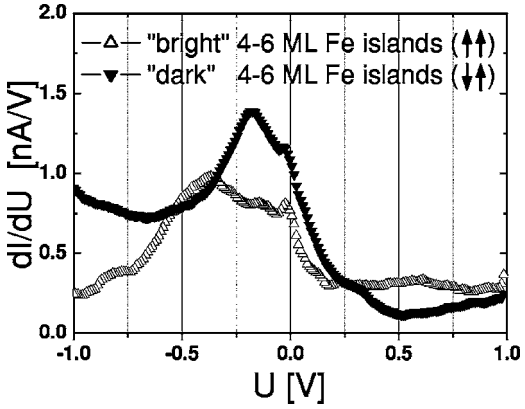

FIG. 5. Spin-resolved dI/dU spectra measured for 4-6 ML thick Fe islands revealing in-plane magnetic contrast, as shown in Fig. 2(d). Spectra were obtained using W/10 ML Au/16 ML Co tips with in-plane magnetic sensitivity.

the tip, the peak at 0.78 eV changes intensity and the position toward lower energies by 0.05 V. The peaks at −0.08 and 0.06 V change intensity, and the peak at 0.2 V almost disappears. Similar features can be found in the DL Fe stripes spectra taken with other tips, as illustrated in Fig. 4(e). This observation confirms the reproducibility of the measurement. Moreover, very similar features, which have been observed in the DL Fe/Mo(110) spectra, can be recognized in the DL Fe/W(110) spectra[26,34,35] with slightly shifted energies, too.

Because the peak at −0.08 V is observed for all tip materials, this peak can be attributed to an occupied sample state, and it is characteristic for the DL Fe on Mo(110) and the DL Fe on W(110).

Similarly to the case of the ML Fe nanostripes, the narrow peaks observed for the DL Fe nanowires change the intensities when switching between parallel and antiparallel orientation of the tip and sample magnetization. Moreover, we observed the shift of the energetic position of the broader feature at 0.78 V. Both observation may be explained in the similar way as for the ML case.

As expected, the spin-dependent differences in the spectra for the ML and DL Fe depending on the relative orientation of magnetization, disappear in the spectra when they are measured using tips with exclusive in-plane magnetic sensitivity (tip D). However, the characteristic features corresponding to different electronic structures for ML and DL Fe areas are observed with tip D, as well.

Spin-resolved spectra for Fe islands as measured with an in-plane sensitive W/Au/Co tips are presented in Fig. 5. In contrast to the ML and DL Fe spectra, these spectra do not show any pronounced peaks for positive voltages. They strongly differ from each other, depending on the relative orientation of the tip and Fe island magnetization. For the antiparallel orientation a large peak at −0.2 V is predominant, whereas for parallel orientation the spectrum reveals a distinct feature at −0.4 V. We tentatively compare the observed features with surface states of bulk Fe(110) because the structure of the few ML thick Fe islands is already very similar to the bulk Fe(110) structure.[17,18] Because of the dislocation network developed in areas thicker than two atomic layers the Fe lattice structure rapidly adopts its bulk values with increasing thickness.[17,18] The peaks might be attributed to Fe(110) surface resonance states, i.e., a minority band state in proximity of the $\Gamma'^{\downarrow}_{2,5}$ point and the majority band state close to the $\Gamma^{\uparrow}_{1,2}$ point,[39] respectively.

IV. CONCLUSIONS

We show that W tips covered by a Au/Co layer can be successfully used in low-temperature spin-resolved STM and STS. Varying the thickness of the magnetic coating of the tip allows to probe the direction of the magnetization in the sample, which is illustrated using different Fe nanostructures prepared on Mo(110). The W/Au/Co tip allows us to detect magnetic patterns with in-plane and out-of-plane contrast at the same sample area. In this way, we demonstrate that the ML and DL Fe nanowires on a Mo(110) crystal are perpendicularly magnetized, and the 3–6 ML thick Fe islands reveal strong in-plane magnetic contrast, indicating a spin-reorientation transition with increasing thickness.

Using W/Au/Co tips, we have performed spectroscopic measurements of ML and DL Fe nanostripes, and thicker Fe islands deposited on Mo(110). We find that the spin-resolved spectra for the ML, DL and thicker Fe/Mo films are different from each other. The spectra taken with the same tip were reproducible. The spin-resolved spectra measured for the ML Fe nanostructures reveal a prominent peak that shows up at $U=+0.38$ V or at $U=+0.42$ V depending on the relative magnetization orientation of the tip and the sample. Spectra for DL Fe stripes obtained using out-of-plane sensitive W/Au/Co tips reveal two large peaks at −0.08 and 0.78 V, and two smaller peaks at 0.06 and 0.2 V. Depending on the relative orientation of the tip and the DL Fe stripe magnetization, the peak at 0.78 eV changes its intensity and position. Spin-resolved spectroscopic data taken with W/Au/Co tips are compared to spectra recorded using W and W/Fe tips, thus being able to distinguish tip-induced from sample-induced features in the spectra. The dI/dU curves obtained for 4–6 ML Fe islands with in-plane magnetization show similarities to results obtained by spin-resolved photoemission spectroscopy, and the spectra are discussed in the terms of Fe(110) surface states.

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