Use of voltage pulses to detect spin-polarized tunneling

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The present letter describes a method to make a spin-polarized scanning tunneling microscopy tip by applying voltage pulses between a W tip and a magnetic sample. This spin-polarized tip has the similar characteristics as an Fe-coated W tip, which was confirmed by observations of antiferromagnetically coupled ferromagnetic Mn(001) layers (>3 ML) grown on an Fe(001) whisker at 370 K. Furthermore, we demonstrate that these voltage pulses can vary the tip magnetization direction. [DOI: 10.1063/1.1556958]

Spin-polarized scanning tunneling microscopy (SP–STM) and spectroscopy (SP–STS) are the most powerful tools for studying surface magnetism at an atomic scale.[1–7] To detect SP tunneling, W tips coated with ultrathin magnetic films,[1–3] tips made of soft magnetic materials whose magnetization can be easily switched,[4] and optically pumped GaAs tips[5–7] have been used. Although the use of tips covered with ultrathin magnetic layers has great advantages compared to the use of bulk magnetic tips with respect to stray field effects[4] and to optically pumped GaAs tips with respect to simplicity,[5–7] it still needs a lot of efforts to prepare these tips for SP tunneling experiments. In this letter we demonstrate that a W tip can detect SP tunneling after voltage pulses have been applied on magnetic materials (''voltage-pulsed tip''). We also show that these voltage pulses can vary the tip magnetization direction.

STM and STS measurements were performed in ultrahigh vacuum ($\sim 5\times 10^{-11}$ mbar) at room temperature with a commercial STM (Omicron UHV STM-1). In this study we compared three kinds of tips: (1) clean W tips (nonmagnetic tips),[8] (2) Fe-coated W tips (magnetic tips),[1–3] and (3) voltage-pulsed W tips. For applying the voltage pulses, we used the Omicron STM software and control unit. During constant current STM topographic measurements (typically, $V_S=1$ V, $I=0.1$ nA), we changed the voltage by means of the control software. After requesting 10 V the actual bias voltage increased from 1 to 10 V within 60 μs. We monitored that the feedback system is too slow to maintain a constant current during this process. We found that it takes about 15 ms to recover the constant current ($I=0.1$ nA) level. Therefore, during this period, the current density was drastically increased, which likely resulted in a tip-sample contact (''tip crash'') or even in a local melting of the tip-sample contact area.[9] Always, mountains with a height of 10–30 nm were observed on the sample surface. Then, we changed the voltage range back to 1 V and moved to a different area. Several processes can occur simultaneously during a voltage pulse,[9] but it is unclear which process dominates. However, clean W tips showed magnetic contrast after application of voltage pulses [Fig. 1]. As samples, we used Mn films (>3 ML) which were grown on an Fe(001) whisker. Previous results with different techniques showed that these Mn films consist

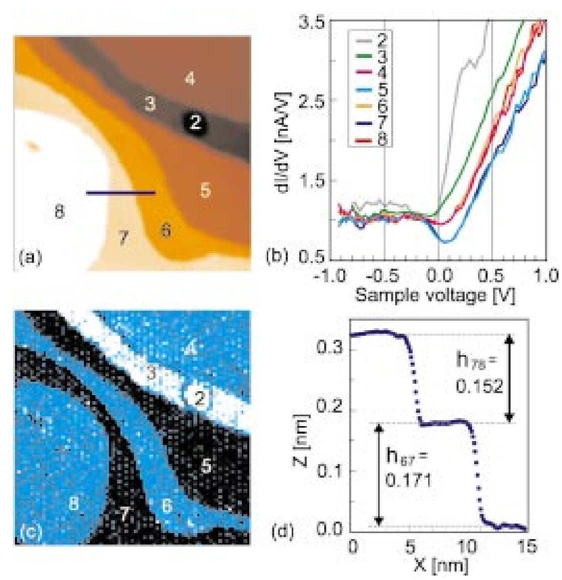

FIG. 1. (Color) SP–STS measurement with the voltage-pulsed tip on Fe(001) covered with 5 ML Mn at 370 K. (a) is a topographic image obtained at a setpoint of $V_S=-0.5$ V, $I=0.5$ nA. Scan size is 50×50 nm^2. Seven different levels are exposed on the surface due to the three-dimensional growth mode. (b) shows the dI/dV curves representative of each level. These curves are averages of typically 10 single curves. Only the lowest level dI/dV curve is a single curve. (c) shows the dI/dV map at +0.1 V measured at the same area as (a). Numbers in (a) and (c) denote the stacking numbers of Mn layers which are deduced from the STS results. (d) shows a line profile across the two steps measured at the black line in (a). h_{ij} indicates the step height between level i and level j.

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of ferromagnetic (001) planes which are antiferromagnetically aligned.[3,10–12] The growth and local electronic structure of the Mn layers on Fe(001) were described in Refs. 8 and 13. STS measurements were performed at every pixel of a constant current topographic image by opening the STM feedback loop at a given current and voltage (''setpoint''). dI/dV curves were obtained by numerical differentiation of the $I(V)$ curves. An external magnetic field was not applied.

Figure 1 was obtained with the voltage-pulsed tip. Figure 1(a) shows a topographic image of the Fe(001) surface after coverage of 5 ML Mn. Seven levels are exposed. Averages of typically 10 dI/dV curves representative of the various layers in Fig. 1(a) are shown in Fig. 1(b). Since the dI/dV curve obtained on the lowest level of Fig. 1(a) is similar to the curve obtained on the second layer,[8] this level can be identified as the second Mn layer. The dI/dV curves obtained on Mn films thicker than four layers show a dip around +0.1 V and a steady increase at positive voltages. The dI/dV curves obtained on the fourth layer are the same as those obtained on the sixth and eighth layer, while the dI/dV curves obtained on the fifth layer are the same as those obtained on the seventh layer. Figure 1(b) also shows that at positive voltages the dI/dV signal is larger on the even layers (i.e., 4th, 6th, and 8th) compared to the odd layers (i.e., 5th and 7th). In the dI/dV map at +0.1 V, the contrast is observed to oscillate with a period of two layers starting from the fourth layer [Fig. 1(c)]. The cross section at the black line in Fig. 1(a) clearly shows the different step heights in Fig. 1(d).[14] The present results obtained with the voltage-pulsed tip are equivalent to those obtained with Fe-coated tips.[3] Furthermore, clean W tips do not show any contrast in dI/dV maps.[3,8] Therefore, it is concluded that voltage-pulsed tips can detect SP tunneling, i.e., voltage pulses can make a nonmagnetic W tip sensitive to the magnetic structures of the sample surface.

The asymmetry obtained from the even and the odd layer dI/dV curves reveals the sample polarization multiplied by the tip polarization,[2] whereas the tip-sample separation dependence is still included.[3] The asymmetry is defined as $A_{dI/dV}=[(dI/dV)_{\mathrm{even}}-(dI/dV)_{\mathrm{odd}}]/[(dI/dV)_{\mathrm{even}}+(dI/dV)_{\mathrm{odd}}]$, where $(dI/dV)_{\mathrm{even}}$ and $(dI/dV)_{\mathrm{odd}}$ are dI/dV curves obtained on the even and the odd layers. Figure 2 shows the asymmetries ($A_{dI/dV}$) at +0.8 V, which were obtained at the setpoint of $V_S=-0.5$ V, $I=0.5$ nA, as a function of the dI/dV value at +0.8 V. The data were obtained with different Fe-coated tips, different clean W tips, and different voltage-pulsed tips.[15] The dI/dV maps obtained with W tips never show magnetic contrast, i.e., $A_{dI/dV}=0$ (triangles in Fig. 2). The dI/dV maps obtained with Fe-coated tips always show a magnetic contrast of 5%–10% (circles in Fig. 2). About 50% of the dI/dV maps obtained with voltage-pulsed tips show a magnetic contrast, i.e., in Fig. 2, 13 data points (some fall on top of each other) reveal a magnetic contrast between 5% and 15% while 13 other data points do not reveal a contrast (<2%). The dI/dV value at +0.8 V is used as the horizontal axis of Fig. 2 since this value indicates the amplitude of the exponential background in dI/dV.[13,16,17] dI/dV values at +0.8 V between 1.5 and 2.5 nA/V for Fe-coated tips and between 2.8 and 4.5 nA/V for W tips are observed, which indicate that W tips have a higher exponential background. One can conclude that this is caused by the lower barrier height of the tip apex of W tips compared to Fe-coated tips. On the other hand, dI/dV values at +0.8 V obtained with voltage-pulsed tips scatter between 1.5 and 5.0 nA/V, i.e., voltage pulses can vary the exponential background. This suggests that when a peak cannot be observed in dI/dV curves due to a high exponential background, this technique can help to resolve the peak by lowering the exponential background as was experimentally shown in Refs. 13 and 17.

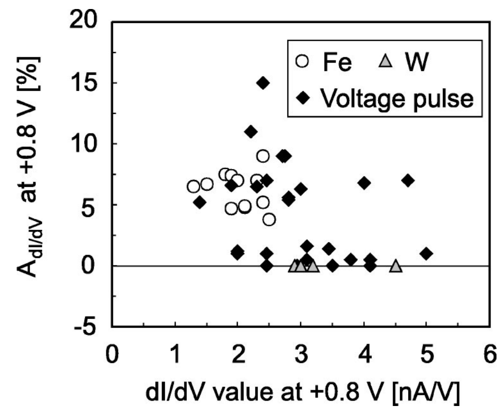

FIG. 2. The asymmetry in dI/dV curves ($A_{dI/dV}$) at +0.8 V obtained on Mn films thicker than three layers are shown as a function of the dI/dV value at +0.8 V. All data shown are obtained from dI/dV curves obtained at a setpoint of $V_S=-0.5$ V, $I=0.5$ nA. Circles, triangles, and diamonds were obtained by different Fe-coated W, different clean W, and different voltage-pulsed tips, respectively.

We found that voltage pulses can change the magnetization direction of the SP tip. Figure 3 shows the dependence of the alternating contrast in the dI/dV maps on the tip condition. Figure 3(a) is a topographic image. Numbers in Fig.

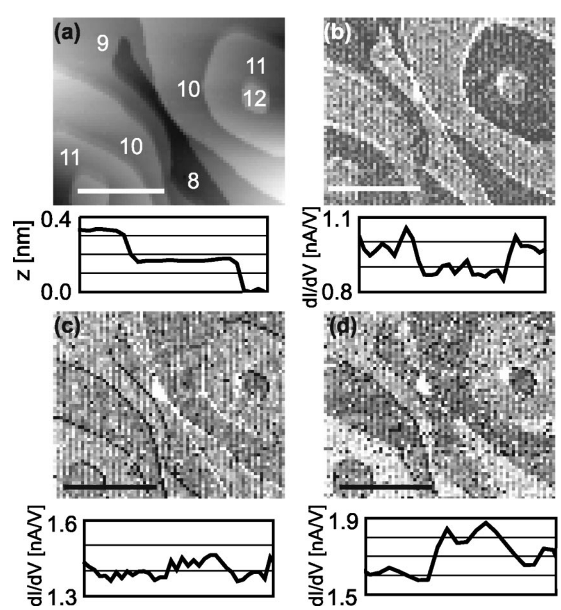

FIG. 3. SP–STS measurements on Fe(001) covered with 9.5 ML Mn at 370 K showing a reversal of the magnetic contrast. (a) is a topographic image obtained at a setpoint of $V_S=-0.5$ V, $I=0.5$ nA. Scan size is 100×80 nm^2. Five different levels are exposed on the surface. Numbers denote the stacking number of the Mn layers. (b)–(d) are dI/dV maps at +0.2 V measured at the same area as (a). Between (b), (c), and (d) the tip was moved ±500 nm away from this area and a voltage pulse was applied. A line profile along the line in (a)–(d) is shown below each image.

3(a) denote the stacking numbers of the Mn layers, which are estimated from a quartz crystal oscillator calibration.[8] Figures 3(b)–3(d) are dI/dV maps at $+0.2$ V, which were measured at the same setpoint ($V_S=-0.5$ V, $I=0.5$ nA) and on the same area as Fig. 3(a). A clear contrast (+5%) can be observed in Fig. 3(b). After the measurement of Fig. 3(b), the tip was moved (>500 nm) to a different area and a voltage pulse was applied. The tip was moved back to the same area as Fig. 3(a), and Fig. 3(c) was measured. The contrast in Fig. 3(c) is almost negligible ($<\pm 1\%$). Again a voltage pulse was applied in the same way; afterwards Fig. 3(d) was measured. Figure 3(d) shows a clear contrast again, but the contrast is inversed (-6%) compared to that in Fig. 3(b). This contrast clearly depends on the tip condition. The variation in the contrast can be explained by different angles between the tip and the sample magnetizations,[2] i.e., the contrast becomes strong when the tip magnetization is parallel or antiparallel to the sample magnetization [Figs. 3(b) and 3(d)] and becomes negligible when the tip magnetization is orthogonal to the sample magnetization [Fig. 3(c)]. These results show that the tip magnetization is not fixed to one direction by, e.g., the stray field of the Fe whisker. The tip magnetization apparently is frozen in immediately after the mass transport from the sample to the tip during pulsing because spontaneous contrast reversals during scanning do not occur.

Magnetic contrasts in SP–STS were found with Fe-coated tips.[1–3] However, the present study showed that W tips can show the same characteristics as Fe-coated tips after applying voltage pulses. These pulses apparently lead to mass transport from the sample to the tip. This results in the tip apex becoming covered with Fe or Mn, thus, giving it magnetic properties. Also, the voltage pulses probably make the tip blunter which is in favor of detection of SP tunneling for systems with an in-plane magnetization.[18] Therefore, this voltage pulsing technique is proposed as an alternative way to prepare SP–STM tips. In our study, we could obtain SP voltage-pulsed tips with a probability of 50% after applying voltage pulses. We also found that this technique can vary the tip magnetization direction and, furthermore, that voltage pulses can vary the background in the dI/dV curves and can change a double tunneling tip to a single tunneling tip (not shown) since voltage pulses can change the chemical composition, shape, and radius of the tip apex.

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