Spin-polarized scanning tunneling microscopy on ferromagnets

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A straightforward approach to spin-polarized scanning tunneling microscopy based on the magnetotunnel effect between a ferromagnetic tip and a ferromagnetic sample is demonstrated. By periodically changing the magnetization of the tip in combination with a lock-in technique, topographic and spin-dependent parts of the tunnel current are separated and the topography and the magnetic structure of the sample are recorded simultaneously. Results are given for polycrystalline Ni and single crystalline Co(0001) surfaces, revealing a high spin contrast, low data acquisition times, and a resolution down to 10 nm. Potentials and limitations of this technique are discussed. © *1999 American Institute of Physics.* [S0003-6951(99)00439-8]

It is one of the ultimate aims of experimental micromagnetism to establish a simple and reliable technique to image magnetic structures down to the atomic level. With techniques like scanning electron microscopy with polarization analysis (SEMPA), photoemission electron microscopy (PEEM), spin-polarized low energy electron microscopy (SPLEEM) or x-ray magnetic dichroism, resolutions of several 10 nm have been achieved. Pushing these techniques to nm resolution is in principle possible, however, it is an enormous experimental undertaking. Even magnetic force microscopy (MFM), which has evolved into a standard technique for magnetic imaging, is limited in resolution to several 10 nm[1] by its underlying physical principle—the dipole interaction of a magnetic tip, of finite size, and finite distance to the surface, with the stray field of a magnetic sample. An alternative scanning technique that intrinsically offers atomic resolution is scanning tunneling microscopy (STM). By using a spin polarized tunneling current, STMs high topographic resolution can be extended to a spin sensitivity of the sample electrons as has been reported a decade ago for setups in air[2] and in ultrahigh vacuum.[3] However, in these early experiments only a mixture of topography and spin dependent contrast was shown and no imaging of the magnetic structure was achieved. A more successful approach[4–6] using optically pumped GaAs tips and a lock-in technique to separate topographic and magnetic information suffers from low contrast and an unintended additional optical contrast. Recently, Bode *et al.* used a magnetic tip to tunnel into the exchange-split surface state of Gd.[7] A magnetic contrast could be obtained from spectroscopic data. However, this method has long data acquisition times and is limited to materials with an exchange-split surface state.

Here we present a straightforward approach to the problem of spin-polarized STM (SpSTM). In the spirit of Johnson and Clarke,[2] we use a magnetic tip to image the sample. We separate the spin-dependent part of the tunnel current by rapidly changing the magnetization of the tip in combination with a lock-in detection of the variations in the tunnel current. This technique is not limited to special materials, offers a high spin contrast of up to several ten percent of the tunnel current, and has fast data acquisition times in the range of ms/pixel.

Experiments were performed in an ultrahigh vacuum chamber ($p=5\times10^{-11}$ mbar) equipped with an Auger electron spectrometer (AES), a differentially pumped sputter gun, and a modified commercially available room temperature STM.[8] Care was taken in the STM design to avoid magnetic parts in the sample stage and scanning unit to allow operation of the STM in an applied magnetic field. Samples as well as magnetic tips were cleaned *in situ* by argon sputtering. Samples were annealed after cleaning by radiative heating to 800 (Ni) and 570 K (Co) to reduce surface roughness and were checked with AES for chemical cleanliness. After sample and tip preparation, tunnel images of the topography were recorded at room temperature. Magnetic contrast was obtained in the following way. By applying an alternating current of frequency f through a small coil wound around the magnetic tip, the longitudinal magnetization of the tip was switched periodically. The tip material, a metallic glass, was chosen to have a low coercivity (<0.5 Oe), vanishing magnetostriction ($<2\times10^{-7}$), low saturation magnetization (≈0.5 T), and low magnetization losses. These parameters allow a rapid switching of the magnetization of the tip without mechanical vibrations of the tip due to magnetostriction or magnetization losses. Furthermore, they minimize the influence of the field of the coil (≈1 Oe) on the sample magnetization. The frequency f was chosen far away from any mechanical resonances of the STM and well above the cutoff frequency of the feedback loop. Variations of the tunnel probability due to the magnetotunnel effect, i.e., maximal probability for parallel and minimal for antiparallel orientation between tip and sample magnetization, result in variations of the tunnel current with the frequency f. These variations were detected with a lock-in amplifier. Since the tip is magnetized along its axis and perpendicular to the sample surface, sensitivity for the perpendicular magnetic component of the sample was obtained. The output signal of the lock-in is referred to as spin-signal in the remainder of the manuscript. For a fixed tip-sample combination, it is proportional to the perpendicular component of the magnetization. However, an absolute value of the sample magnetization cannot be obtained. For all images and line scans of the spin

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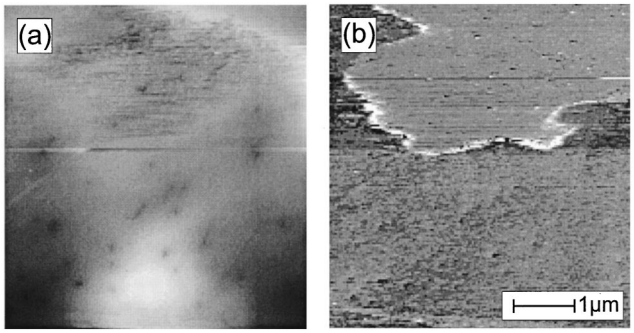

FIG. 1. STM images of the topography (a) the magnetic domain structure of the same area (b) of polycrystalline Ni. Sample bias: 0.13 V; tunneling current: 1 nA; (a) height variations 3 nm; (b) spin contrast: 2.2%.

signal shown here, the reversal frequency f was chosen between 40 and 80 kHz and integration times τ of 3 m/pixel were used. Initial tests of the setup on paramagnetic Cu(100) showed no spin signal.

On large, several μm^2 scans of Ni surfaces, strong contrasts can be found in the spin signal as displayed in Fig. 1(b). The image of the spin signal shows two regions, i.e., domains, with different intensity, separated by a fine, bright line, i.e., a domain wall. The observed features in the spin signal are not related to the topographic features of the same area as can be seen when comparing the topography of Fig. 1(a) with the spin signal of Fig. 1(b). This excludes that the observed features are caused by a cross-talk from the topography. Moreover, the spin signal is changing on the time scale of hours during repeated scanning, which rules out that the contrast is caused by some other, static characteristic like compositional, structural, or orientational variations of the sample surface. To rigorously prove the magnetic origin of the observed contrast, the influence of a magnetic field on the features in the spin signal was studied. Similarly to Ni, also on single crystalline surfaces of Co(0001), lines separating domains of different contrast are found (see Fig. 2). On Co(0001) the observed features show only minor changes even after extended scanning of the same area. This is probably related to the higher magnetic stiffness of Co in comparison to Ni, minimizing the influence of the magnetic field of the tip on the sample. When applying a short pulse of a homogeneous magnetic field of the order of 50 Oe perpendicular to the sample surface as indicated by an arrow in Fig. 2, the observed line can be moved a couple of μm during scanning while no movement is observed in the topographic image. This unambiguously proves the magnetic origin of the spin signal. Hence, we indeed observe magnetic domains and domain walls on the surfaces of Ni and Co. Since the magnetic field used to move the domain wall is much larger than the alternating field used to switch the magnetization of the tip, the tip magnetization is fixed for the duration of the pulse. Thus, during the short magnetic pulse the lock-in signal is lost for several scan lines and neither domain walls nor domains are observed in the part of Fig. 2 that is indicated by the arrow.

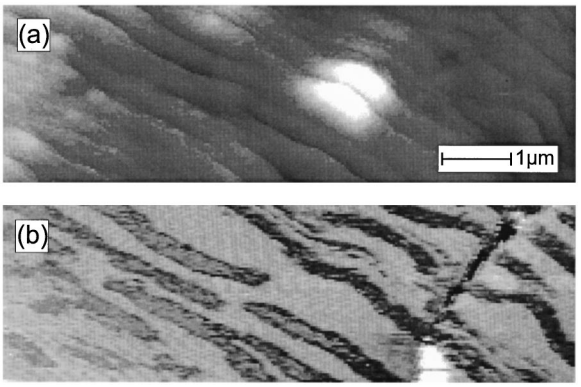

FIG. 3. STM images of the topography (a) the magnetic domain structure of the same area (b) of Co(0001). Sample bias: 0.2 V; tunneling current: 0.5 nA; (a) height variations 4 nm; (b) spin contrast: 3.6%.

To estimate the lateral resolution of the spin signal, we focus on the domain walls. For polycrystalline Ni samples, the observed domain wall width is between 100 and 150 nm in qualitative agreement with calculated wall widths of 85-200 nm depending on the crystal orientation.[9] Line scans across Ni domain walls (not shown) reveal a lateral resolution of $\approx$25 nm. A higher resolution can be demonstrated on Co(0001) due to the smaller wall width. As displayed in Fig. 3(b), Lifshitz closure domains[10] on the micron scale are observed. Due to a small miscut of the sample surface, step bunches of 1-2 nm height and $\approx$500 nm separation are found as illustrated in Fig. 3(a). Most of the observed closure domains are pinned at these step bunches giving an alternating surface magnetization on adjacent flat regions. Figure 4 displays a line scan across a domain wall separating two domains of opposite contrast. Neighboring data points in the

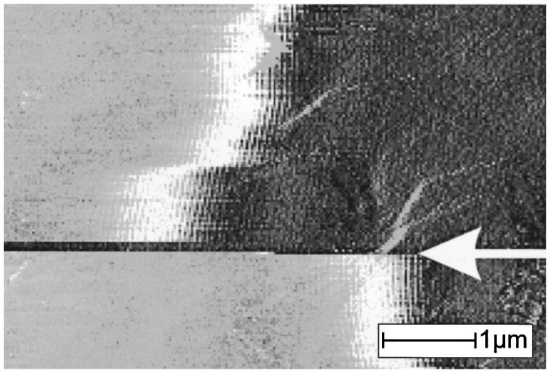

FIG. 2. STM image of a domain wall at the surface of Co(0001). When applying an external magnetic field pulse of 50 Oe (indicated by the arrow), the domain wall is moved to the left during scanning. Sample bias: 0.2 V.

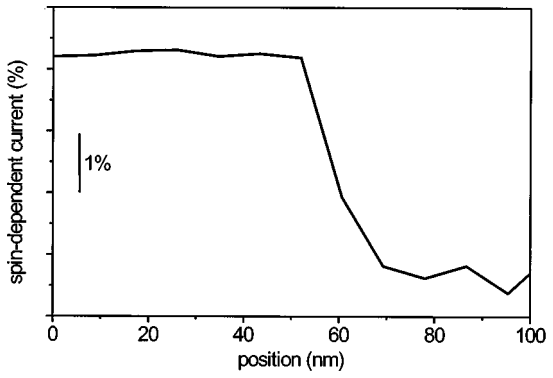

FIG. 4. Line scan across a domain wall between two domains of opposite contrast on Co(0001). The displayed data is raw data of a single scan and was recorded in $\approx$100 ms.

scan are separated in time by more than 2τ to avoid correlations due to the integration in the lock-in amplifier. The scan (raw data) reveals a wall width of ≈ 17 nm in good agreement with the estimated width of a 180° Bloch wall for Co of 15.7 nm.[9] However, one has to keep in mind that in the closure domain pattern of Co(0001) tilted Bloch walls of lower angles are present[11] that might modify the domain wall thickness slightly. The line scan reveals a lateral spin resolution of about 10 nm. Hence, the present resolution is basically limited by the sharpness of the available magnetic structures. This high lateral resolution is obtained in combination with short data acquisition times and a relatively large contrast. The line scan of Fig. 4 was recorded in only ≈ 100 ms. At room temperature, the highest spin contrast was obtained with freshly prepared tips and gap voltages below ± 0.1 V: 11% for Ni and 26% for Co. This is in good agreement with values measured in planar tunneling junctions.[12,13]

Due to the close proximity of the tunneling tip to the sample, magnetic dipole interaction between these two ferromagnets cannot be neglected in all cases. For freshly prepared and sharp tips, no significant modification of the domain structure of Co(0001) by the tip was observed. However, in the case of dull tips, i.e., tips that suffered from repeated tip crashes, we observe an influence of the magnetic field of the tip on the domain walls. The walls rapidly vibrate with the magnetization frequency *f*, such that the resolution is limited to several 100 nm (as in Fig. 2). However, this interaction can also be used to locally measure the magnetic susceptibility of a sample. Especially for structured soft magnetic materials, this still allows one to measure spin polarization in the susceptibility mode by detecting higher harmonics of the magnetization frequency *f* in the tunneling current.

In conclusion, we have demonstrated a simple and straightforward method to obtain magnetic information with STM. By using a magnetic tip and a lock-in technique to separate the spin-dependent from the distance-dependent tunneling current, the topography and the magnetic structure of a ferromagnetic sample have been recorded simultaneously. The domain structure of polycrystalline Ni and single crystalline Co(0001) surfaces have been observed with high spatial resolution. The magnetic origin of the observed signals has been rigorously proven. Due to the close proximity of the ferromagnetic tip to the surface, this technique is limited to study the domain structure of sufficiently hard magnetic materials relative to the magnetic hardness of the tip. In soft magnetic materials, however, the local susceptibility may be studied.

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