collapse of the depletion region in the LR state. Our model of separate occupancies for electrons and for holes and of minority-carrier trapping at the GB states could account for the observed transition. There may well be other mechanisms in operation and this possibility is not discounted here.

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Observation of magnetic forces by the atomic force microscope

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We present a new way to observe the surface domain distribution of a magnetic sample at a submicrometer scale. This magnetic microscopy is based on the idea of measuring magnetic forces with the recently developed atomic force microscope (AFM). We study the magnetic forces involved in the interaction between a single-domain microtip and the sample surface magnetic domains. The influence of the experimental conditions on the performance of the AFM as a magnetic profiling device is also discussed. Preliminary experimental results are reported.

One of the most challenging problems nowadays in several laboratories using scanning tunneling microscopy[1] (STM) is the characterization of the magnetic properties of surfaces. It would be very interesting to observe, with very high resolution, the surface domain structure of materials of interest in magnetic information technology.[2] We believe that it is not simple to solve this problem with the STM. To observe a domain wall we should perform (x,y) scans of ≈ 0.01–$1\ \mu$m. The variation of current (or tip-sample distance z), when the STM is operated in the constant z (or constant current) mode, is expected to be of $\approx 10\%$[3] (or, at most, ≈ 1 Å). It is possible that in this case the surface topography will hide these tiny effects. There is no way, given the irregularities and surface defects observed in STM experiments, to distinguish ≈ 1-Å tip displacement associated to a change in the spin configuration in the surface when the tip scans over several hundred nanometers. We present in this communication a way of observing magnetic domain structure based on the idea of measuring magnetic forces with an atomic force microscope[4] (AFM). In the AFM technique a sharp tip attached to a tiny cantilever is used to map the contours of a sample surface. Instead of measuring the current as in STM, the force between tip and sample is used as the control parameter. Forces are detected by measuring the deflection of the lever. This paper presents a theoretical analysis of the finger prints of the magnetic forces and the associated motion of the cantilever for different spin configurations. The influence of some experimental conditions in the performance of the AFM as a magnetic profiling device is also discussed. As we will see, domain resolutions of the order of 0.01 μm can be achieved with this technique, even on rough surfaces. Preliminary experimental results that appear to prove the theoretical proposals are reported.

In the magnetic version of the AFM, images are obtained by measuring the interaction force between a single-domain magnetic microtip and a magnetic sample. When the tip is moved parallel to the surface, it will follow the changes of the normal component of the tip-sample force. The interaction force can be estimated by assuming a direct interaction between the permanent magnetic moments $\bar{\mu}_1$ and $\bar{\mu}_2$, per unit volume, corresponding to the tip and sample, respectively. Provided the gap distance z between tip and sample is larger than say ≈ 10 Å, the interatomic forces can be neglected as long as we are considering a tip with a radius of the order of nanometers[5] (these kind of forces should be taken into account for very large macroscopic-tip radius[6]). Within these approximations, the normal force F, acting on the tip, will be given by

$$F(z) = \int_{\text{tip}} d^3\bar{r}_1 \int_{\text{sample}} d^3\bar{r}_2 f_z(\bar{r}_1 - \bar{r}_2), \qquad (1a)$$

where $f_z(\bar{r})$ is the interaction force between two magnetic dipoles, $\bar{\mu}_1$ and $\bar{\mu}_2$, at a distance $\bar{r} = \bar{r}_1 - \bar{r}_2$:

$$f_z(\bar{r}) = \left(\frac{\mu_0}{4\pi}\right)\frac{\partial}{\partial z}\left(\frac{3(\bar{r}\bar{\mu}_1)(\bar{r}\bar{\mu}_2)}{r^5} - \frac{(\bar{\mu}_1\bar{\mu}_2)}{r^3}\right), \qquad (1b)$$

and μ_0 is the vacuum permeability. Because of the dipolar behavior of the magnetic force given by Eq. (1), when the tip is over a region of uniform magnetization (constant magnetic field), there is not normal force acting on it. The forces

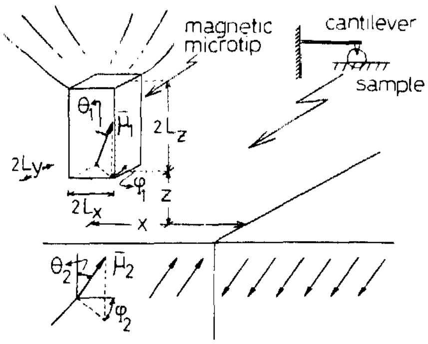

FIG. 1. Scheme of the magnetic version of the atomic force microscope.

manifest themselves when the tip approaches a domain wall separating two regions of different magnetizations (in general, any region of nonuniform magnetization). The main features of the force acting on the tip as it goes across a domain wall can be illustrated with the simple model sketched in Fig. 1, where we consider two infinite antiparallel domains separated by a sharp domain wall. The force distribution around the domain wall will depend on the orientations of the tip and sample magnetizations, characterized by the angles θ_1, φ_1 and θ_2, φ_2, respectively. A very important point associated with the long-range force given by Eq. (1) is that, as long as the size L of the single-domain particle at the end of the tip is large compared to the gap distance z, the tip force does not depend on z. Therefore, one can work at relatively long distances from the surface and in contrast with the STM, it is not necessary to have a well-defined z value. By assuming a spherical magnetic tip (with a radius $L \gg z$), the tip sample force as a function of the tip distance x to the domain wall takes the simple form

$$F(x) = F_0(ax_r + b)/(x_r^2 + 1), \quad (2)$$

where $x_r = x/L$ and $F_0 = 8/\pi \mu_0 \mu_1 \mu_2 L^2$; a and b are constants that depend on the spin configuration. In Fig. 2 we have plotted the reduced force F/F_0 as a function of x_r for different spin configurations. These results are obtained for a spherical magnetic tip, but can be generalized to an arbitrarily shaped single-domain particle used as the tip. For example, we have calculated the forces induced on a needlelike tip like that shown in Fig. 1. Our results show that Eq. (2) remains approximately valid, provided $L^2 = L_x L_y$, $x_r = x/L_x$, and $L_z \gg z$. In Fig. 2(d) we have plotted the calculated force or tip displacement profile assuming different wall widths ξ.[7] Provided the domain wall width ξ would be of the order or higher than L, it would be possible to get information, not only of the domain distribution on the sample surface, but also of the domain wall itself. An interesting point is that the AFM would be able to obtain information about the thermodynamic properties of a magnetic sample through the dependence of ξ (or the magnetic correlation length) and μ with the temperature. From this point of view, we can interpret Fig. 2(d) as the expected behavior of an AFM profile as the temperature increases.

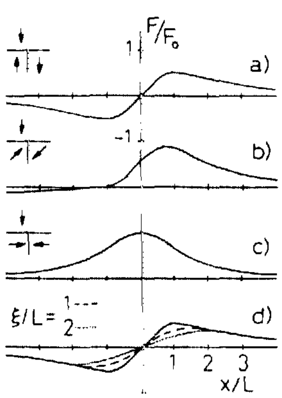

FIG. 2. Calculated forces F/F_0 vs the distance x/L between a spherical tip and a domain wall separating two antiparallel domains for different spin configurations. (a)–(c) correspond to a sharp domain wall. (d) is the same as (a), but for different wall widths ξ/L.

To simulate the influence of these forces in an AFM experiment, consider that the base of the lever is kept fixed with respect to the sample. When the tip approaches a domain wall, it will suffer a normal displacement given by the solution of $K(d-z) + F(x,z) = 0$, K being the force constant of the lever and d the tip-sample distance in the absence of forces. In our case the displacement Δz will be given by $\Delta z = F/K$, and is independent (for $L_z \gg z$) on the exact distance between tip and sample. This is very important, because the magnetic AFM will not be sensitive to the surface roughness, as long as the surface roughness is small compared to L_z. Another point is that Fig. 2 could be taken approximately as a plot of the tip displacement that would be observed in an experiment, just by noting that $F/F_0 = \Delta z/\Delta z_0$, $\Delta z_0 = F_0/K$ being the maximum amplitude of the displacement. The sensitivity of the AFM will be controlled by the magnitude of Δz_0 with respect to the amplitude of thermal oscillations, $\Delta z_T \approx \sqrt{(K_B T/K)}$. Taking μ_1 and μ_2 typically of the order of a Bohr magneton μ_B per atom, we have $F_0 \approx 10^{-14} L^2$ N and $\Delta z_0 \approx 10^{-4} L^2/K$ Å (K given in N m^{-1} and L in Å). At room temperature the condition $\Delta z_0 > \Delta z_T$ is equivalent to a condition that relates the force constant of the lever K and the lateral dimensions of the magnetic tip: $K < 10^{-8} L^4$ N m^{-1} (L in Å). By assuming that this sensitivity condition is satisfied, the most useful measure of the performance of the AFM as a magnetic profiling device will be the lateral resolution parallel to the surface. In other words, what is the minimum domain size D which can be distinguished with this technique? A measure of this resolution could be the width of the region in which the force changes as the tip goes across a domain wall. As we have seen, this characteristic length is of the order of the lateral tip dimension in the scanning direction L. From the sensitivity condition given above, we see that the force constant of the lever imposes a lower limit to the AFM lateral resolution. For example, for typical force constants $K \approx 0.01$–1 N m^{-1} we would have $L_{min} > 50$–100 Å (or forces $F_0 > 10^{-11}$–10^{-10}N).

We have tried to measure magnetic forces with our AFM,[8] which is operated in air. In order to simulate the situation presented in Fig. 1, we have chosen a ferromagnetic Ni foil as a sample and an electrochemically rolled and etched Ni lever with an integrated ferromagnetic tip. As an

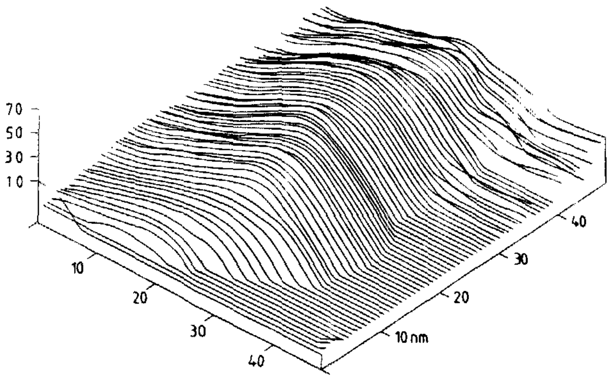

FIG. 3. Deflection of the lever is plotted as a function of the tip position on the Ni sample. The interaction force between sample and lever was attractive. The AFM was operated in the constant force mode, i.e., the displayed lines are equiforces lines.

example of various measurements, Fig. 3 shows the obtained line scans, which are very similar to the asymmetric lines shown in Fig. 2(b). The interaction force in this case was attractive. The right side of the scans in Fig. 3 are flat, indicating that small forces are out of apparatus resolution. We have checked very carefully the topography of this Ni foil by STM measurements, also performed in air. Typical structures have a height of 5–10 nm. However, the structures observed by magnetic interactions (Fig. 3) show a deflection of the cantilever beam in the range of 60 nm. Therefore, no correlation between the height of the structures in the topographic and magnetic images is observed. It is very difficult to calculate the force constant of the lever K because of the unknown elastic constant of rolled and etched thin ferromagnetic Ni foil used as a lever and the effects arising from the interactions within the tunneling junction.[4,9] Nevertheless, from the width of the structure in Fig. 3, we estimate a monodomain tip of $L \approx 500$ Å (i.e., a maximum force $F_0 \approx 10^{-14} L^2 \approx 3\times 10^{-9}$ N) and from the deflection of the cantilever beam $\Delta z_0 \approx 500$ Å, we obtain $K \approx 0.05$ N m^{-1}, which satisfy very well the sensitivity condition of the AFM versus thermal oscillations. By taking into account the roughness of the estimation, the order of magnitude of K seems to be a reasonable value in comparison with others reported before in AFM experiments ($\approx$0.05–0.2 N m^{-1}).[4] Our experimental results show a good reproducibility for the repulsive as well as the attractive interaction between tip and sample. Since these interactions can be observed for a wide range of tip-sample separation (more than 10 nm), we conclude that we measure long-range forces, which cannot be attributed solely to the attractive van der Waals forces. This strongly suggests the magnetic nature of the observed interaction. Finally, we would like to add that we were also able to observe oscillating force-sample position curves. These experiments were performed on rapidly quenched Fe-Nd-B samples, where the domain size is known to be much smaller than the typical sizes (0.1–2 μm) in Ni.

In conclusion, we have presented a new method to obtain information about local surface magnetic properties, based on the idea of measuring forces with an atomic force microscope. We have studied the forces involved in an AFM experiment and their relation to the magnetic topography, depending on different spin configurations in the sample surface, and also the performance of the AFM as a magnetic profiling device. We have shown theoretically that with our magnetic version of the AFM, it is possible to observe domain walls and the domain distribution for a magnetic sample, as well as to get information about its thermodynamic properties. Lateral domain resolutions of the order of 0.01 μm can be achieved with this technique. We have presented preliminary experimental results that show the sensitivity of our AFM to magnetic interaction. The magnetic version of the AFM opens a new field with the possibility of resolving magnetic domain structures on the submicrometer scale.

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