Quantitative interpretation of magnetic force microscopy images from soft patterned elements

J. M. García,^{a)} A. Thiaville, and J. Miltat

Laboratoire de Physique des Solides, University of Paris-Sud and CNRS, Orsay, France

K. J. Kirk^{b)} and J. N. Chapman

Department of Physics and Astronomy, University of Glasgow, Scotland, United Kingdom

F. Alouges

Laboratoire de Mathématique, University of Paris-Sud and CNRS, Orsay, France

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By combining a finite element tip model and numerical simulations of the tip-sample interaction, it is shown that magnetic force microscopy images of patterned soft elements may be quantitatively compared to experiments, even when performed at low lift heights, while preserving physically realistic tip characteristics. The analysis framework relies on variational principles. Assuming magnetically hard tips, the model is both exact and numerically more accurate than hitherto achieved. © 2001 American Institute of Physics. [DOI: 10.1063/1.1389512]

Magnetic force microscopy (MFM)^{1,2} is now a widely disseminated technique aimed at imaging the micromagnetic structure of ferromagnetic materials. In the best cases, it allows for ≈ 20 nm lateral resolution with minimal sample preparation but with the drawback of a difficult quantitative analysis of the actual magnetization distribution. Early experiments³ demonstrated a clear relation between charge distribution and MFM contrast. Such findings were subsequently formalized by Hubert *et al.*⁴ and, despite being questionable, it is now generally assumed that MFM primarily is a charge mapping microscopy. Experiments performed on soft magnetic materials, especially, however clearly reveal the occurrence of tip induced perturbations.^{5–9} Such difficulties may partly be alleviated when recording MFM images with low moment tips and large tip-sample distances,¹⁰ at the potential expense, however, of sensitivity and/or lateral resolution. Even then, probe induced switching has been observed under field.¹¹ In this letter, we investigate, both experimentally and theoretically, the MFM imaging process and introduce a simple framework allowing for its quantitative interpretation.

The observed samples are thermally evaporated $\text{Ni}_{80}\text{Fe}_{20}$ elements, 16 nm thick, prepared by electron-beam lithography and lift-off patterning on a Si_3N_4 membrane. The MFM experiments have been performed using a NanoScopeTM microscope operated in the tapping/lift mode¹² and equipped with frequency detection. To first order, the frequency shift Δf is directly related to the force gradient according to: $2k\Delta f/f = -\delta F/\delta z$, f being the cantilever resonance frequency and k its spring constant. The probes were commercial Si cantilevers from NANOSensorsTM having $f \sim 80$ kHz and $k \sim 5$ N/m mean characteristics. The tips were sputter coated with a $\text{Co}_{80}\text{Cr}_{20}$ nominal composition alloy and magnetized along their pyramid axis prior to the experi-

ments. We have found that only a tiny coating thickness range allows for successful imaging: if the $\text{Co}_{80}\text{Cr}_{20}$ layer is thinner than ≈ 15 nm, no magnetic contrast appears, whereas a coating thicker than ≈ 30 nm gives rise to a sole strong uniform attractive contrast. Consequently, meaningful observations requires finely selected tip moments. The images presented in this letter have been acquired with a tip having a coating ≈ 20 nm thick.

In the absence of tip-sample interaction, the $2\text{ }\mu\text{m}$ -sized square elements should exhibit a perfect Landau-Lifshitz-type flux closure structure. However, if the tip-sample distance z_{tip} is kept small in order to ensure a good lateral resolution, the MFM images systematically display an apparent domain wall curvature producing a picture reminiscent of a four-bladed propeller (Fig. 1). This apparent curvature proves insensitive to the scanning direction as demonstrated in Figs. 1(a) and 1(b), precluding any nonequilibrium effect

FIG. 1. MFM images of a $[2\text{ }\mu\text{m} \times 2\text{ }\mu\text{m} \times 16\text{ nm}]$ permalloy element. Lift height is $z_{\text{tip}} = 20$ nm except where mentioned. Conditions are: (a) Tip scanned from left-hand side to right-hand side (trace), (b) tip scanned from right-hand side to left-hand side (retrace), (c) reversed tip magnetization, and (d) lift height 45 nm and tip magnetization as in (c).

^{a)}Electronic mail: garcia@lps.u-psud.fr

^{b)}Present address: Electronic Engineering and Physics Division, Univ. of Paisley, Scotland, UK.

FIG. 2. (a)–(c) Calculated magnetization distribution (lateral cell size: 4 nm) of a $[1 \mu\text{m} \times 1 \mu\text{m} \times 16 \text{ nm}]$ permalloy square element for different tip positions as indicated by markers: (a) the tip is located in the middle of a domain, (b) the tip is near the right-hand side of one domain wall, (c) the tip is near the left-hand side of the same domain wall are shown. The gray scale represents $\text{div}\mathbf{M}$. (d) Simulated MFM image of a $[1 \mu\text{m} \times 1 \mu\text{m} \times 10 \text{ nm}]$ element taking due account of tip-sample interactions. The gray scale now represents $-\delta F/\delta z$. The vortex core magnetization is parallel to the tip magnetization. Simulation parameters are lift height 27.5 nm, effective monopole height above the sample midplane 60 nm, and effective pole strength $0.145 \text{ mT } \mu\text{m}^2$.

in the MFM image acquisition process. When the tip is magnetized in the opposite direction, the apparent curvature is inverted [Fig. 1(c)]. Although the perturbation decreases with increasing z_{tip} , it can still be distinguished for a 45 nm lift height [Fig. 1(d)], in agreement with previous work.¹⁰ Moreover, we have observed that, for a given tip magnetization, some elements exhibited a certain apparent domain wall curvature whereas others displayed an opposite curvature, a phenomenon to be safely correlated to the sense of rotation of their magnetization [clockwise (cw) or counter clockwise (ccw)], as explained next.

Were the tip to be recessed to infinity, the sample would exhibit a flux closure structure with four triangular domains and a central vortex, the magnetic charges being mainly concentrated along the domain walls. Figures 2(a)–2(c) display the magnetization distribution within a $1 \mu\text{m}$ square element for various tip locations above the sample together with a gray-level representation of $\text{div}(\mathbf{m})$ according to micromagnetic simulations. The element size had here to be kept small because of computation time constraints for full image simulation [Fig. 2(d)]. The tip magnetization points downwards so that charges $\rho = -\text{div}(\mathbf{m})$ building up within the sample under the influence of the tip stray-field¹³ screen tip charges. When the tip approaches one of the domain walls, induced charges interact with the nearest charges inherent to the wall. Attraction appears if the charges have opposite signs [Fig. 2(b)], whereas repulsion occurs in case the charges bear the same sign [Fig. 2(c)]. Obviously, if the tip magnetization is reversed, the induced charges are now positive and the wall distortion is inverted. A similar result is obtained if, instead of reversing the tip magnetization, the intrinsic wall charges are reversed by changing the sense of rotation of the magnetization from cw to ccw, or vice versa.

A MFM image is the result of a complex convolution process. The force is equal to the energy gradient. Hence, for

each tip position, a numerical evaluation of the second derivative of the overall micromagnetic energy, including the sample self-energy, yields the force gradient and so the frequency shift. Variational principles, however, offer a more elegant and numerically more precise approach. Let us call $\mathbf{H}_{\text{tip}}$ the stray field arising from the tip at the sample and $\mathbf{M}_{\text{sample}} = M_s \mathbf{m}$ the sample magnetization distribution at equilibrium, M_s being the saturation magnetization and $\mathbf{m}$ a local unit vector. In the limit of a magnetically hard tip and assuming an infinitesimal variation δz_{tip} of the tip-sample distance, and precisely because $\mathbf{M}_{\text{sample}}$ has reached its equilibrium configuration, the virtual work done by $\mathbf{m}$ is simply given by:

$$\delta E = -\mu_0 M_s \left[\int_{\text{sample}} \left[\frac{\partial \mathbf{H}_{\text{tip}}}{\partial z} \cdot \mathbf{m} \right] d^3 r \right] \delta z_{\text{tip}}. \quad (1)$$

The force between the tip and the sample in the vertical direction is then $F_z = -\delta E/\delta z_{\text{tip}}$ and as a consequence the force gradient reads:

$$\frac{\delta F_z}{\delta z_{\text{tip}}} = \mu_0 M_s \left\{ \int_{\text{sample}} \left[\frac{\partial^2 \mathbf{H}_{\text{tip}}}{\partial z^2} \cdot \mathbf{m} \right] d^3 r + \int_{\text{sample}} \left[\frac{\partial \mathbf{H}_{\text{tip}}}{\partial z} \cdot \frac{\delta \mathbf{m}}{\delta z_{\text{tip}}} \right] d^3 r \right\}. \quad (2)$$

The first term on the right-hand side of Eq. (2) may look familiar to the reader: if $\mathbf{m}$ were replaced by $\mathbf{m}_0$, i.e., the configuration in the absence of $\mathbf{H}_{\text{tip}}$, the expression would be equivalent to that widely used in the literature for nonperturbative MFM. On the other hand, the second term of Eq. (2) takes into account the variation of the magnetization distribution within the element as a function of lift height when immersed in the tip stray-field gradient. Such a contribution plays a significant role when imaging soft magnetic materials. Equation (2) solely requires the evaluation of the first order derivative of $\mathbf{m}$ vs z_{tip} and is thus prone to high numerical accuracy.

Despite being concise, Eq. (2) proves useful only if the tip stray-field distribution may be known. In order to evaluate the latter, a finite element micromagnetic model of the tip has been developed. As a simplest model, a conical shell with zero net charge defines the magnetic part of the tip. The effective tip length¹⁴ has been arbitrarily chosen to be equal to $50w$, where w is the coating thickness. Although anisotropy alone favors a perpendicular easy magnetization axis, its moderate amplitude ($\mu_0 M_s^2/4$) ensures that the magnetization remains essentially parallel to the cone generatrix except in the vicinity of the apex. Figure 3 summarizes the essential results of the model, namely: (i) For a given lift height, the field distribution, whether axial or radial, proves extremely similar to that of a monopole [Fig. 3(a)]. (ii) The effective monopole height increases linearly with increasing lift height, with slope >1 [Fig. 3(b)]. This means that the field distribution broadens faster than that of a monopole whose position would be fixed within the tip. It proves almost insensitive to the CoCr alloy thickness within the range of interest as if it were merely governed by the tip geometry. (iii) The decay of the field amplitude due to the monopole position shift is partly compensated by an increase of the

FIG. 3. Conical shell tip model: (a) example of a comparison between computed tip stray-field (symbols) and monopole (lines) distributions: lift height 25 nm, CoCr thickness $w=20$ nm, CoCr saturation magnetization 30 mT, (b) effective monopole height (circles) and strength (squares) vs lift height for $w=20$ nm (large symbols) and $w=10$ nm (small symbols) are presented. Open and full symbols refer to the axial and radial field components, respectively.

effective pole strength with growing lift height [Fig. 3(b)]. In distinction to the effective height, the pole strength depends strongly on the CoCr thickness.

It proves particularly stimulating that, letting the thickness dependence aside, these conclusions basically agree with recent experimental data.¹⁵ The maximum axial field values also comply with published data.^{16,17} Therefore, in the following, the tip stray field has been assumed to be monopole-like and obey laws displayed in Fig. 3. Only one fitting parameter has been retained, namely the pole strength. In doing so, one may adjust the overall attractive force between the sample and tip so that a realistic spring constant relates the force gradient and the frequency shift.

Figure 2(d) shows a simulated MFM image for $[1 \times 1 \mu\text{m}^2]$ element exhibiting excellent qualitative agreement with Fig. 1(c). Quantitative comparison is provided in Fig. 4 (profile labeled b) where the measured data [frequency shifts corresponding to trace AB in Fig. 1(c)] have been transformed into equivalent force gradients using $k=5.2$ N/m. Simulation parameters read: $[2 \mu\text{m} \times 2 \mu\text{m} \times 16 \text{ nm}]$ element size, 20 nm lift height, 53 nm effective monopole height above the sample midplane, $\approx 0.083 \text{ mT } \mu\text{m}^2$ pole strength, giving rise to a maximum axial field of $\approx 30 \text{ mT}$ at the sample midplane level. The present simulations not only correctly predict the apparent wall locations but also their apparent width.¹⁸ It is worth comparing our results with previous models. If instead of the total energy, only the interaction energy (Zeeman) is taken into account to calculate the force gradient,¹⁹ the profile 4a is obtained. In this case, the predicted curve exhibits larger amplitudes and apparent wall transitions sharper than those measured. On the other hand, line 4c represents the results considering the standard no perturbation approach [only the first term of Eq. (2) with $\mathbf{m} = \mathbf{m}_0$ is then used]. The latter profile neither predicts the global attractive force nor the apparent wall location shift due to the tip influence.

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FIG. 4. Experimental (dots) and theoretical (continuous line) force gradient profiles along one scan line located at one quarter of the element height [trace AB in Fig. 1(c)] are shown. The theoretical profiles (permalloy: $[2 \mu\text{m} \times 2 \mu\text{m} \times 16 \text{ nm}]$, lift height 20 nm, effective pole strength $0.083 \text{ mT } \mu\text{m}^2$) were calculated as follows: (a) including the Zeeman energy only, (b) using Eq. (2), and (c) taking into account the sole first term of Eq. (2) (no-perturbation limit). Dashed and dotted lines mark the edges of the sample and wall image location in the no-perturbation limit, respectively.

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