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Magnetic elements for switching magnetization magnetic force microscopy tips

V. Cambel [a,*], P. Eliáš [a], D. Gregušová [a], J. Martaus [a], J. Fedor [a], G. Karapetrov [b], V. Novosad [b]

[a] Institute of Electrical Engineering, Slovak Academy of Sciences, Dubravska cesta 9, 841 04 Bratislava, Slovakia
[b] Materials Science Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439, USA

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ABSTRACT

Using combination of micromagnetic calculations and magnetic force microscopy (MFM) imaging we find optimal parameters for novel magnetic tips suitable for switching magnetization MFM. Switching magnetization MFM is based on two-pass scanning atomic force microscopy with reversed tip magnetization between the scans. Within the technique the sum of the scanned data with reversed tip magnetization depicts local atomic forces, while their difference maps the local magnetic forces. Here we propose the design and calculate the magnetic properties of tips suitable for this scanning probe technique. We find that for best performance the spin-polarized tips must exhibit low magnetic moment, low switching fields, and single-domain state at remanence. The switching field of such tips is calculated and optimum shape of the Permalloy elements for the tips is found. We show excellent correspondence between calculated and experimental results for Py elements.

1. Introduction

Since its introduction [1,2] scanning probe magnetic force microscopy (MFM) has become the state-of-the-art tool used to study submicron magnetic domain structures and written bit patterns in recording media [3,4], internal currents in conductors of integrated circuits [5], vortex lattices in superconductors[6,7], etc. MFM is popular for its relatively high spatial resolution (∼50 nm), high sensitivity and its ubiquity in variety of surface conditions. The MFM can be performed in variety of different modes: constant height mode, constant frequency shift mode [8], or most popular, combined tapping/lift mode [9].

The spatial resolution of the MFM is closely related to the magnetic properties of the tip and the sample, but ultimately it is limited by the need of force deconvolution. The magnetic interaction between the tip and the sample is mixed with other tip–sample interactions, such as electrostatic (Coulomb) and atomic (van der Waals). The electrostatic forces are long-range, and van der Waals forces dominate at very short distances, but they are also present at larger distances.

Magnetic force deconvolution is usually obtained by performing two measurements at different heights in each point of the sample. Most popular and fast implementation of this algorithm is the so-called lift-mode method: a two-pass scan of each line, developed to distinguish the magnetic and non-magnetic interactions. Within the first pass the tip maps the sample topography in the AFM tapping mode. In the second pass the tip scans the same topography profile but lifted by pre-determined distance (lift distance). The common premise is that in the second pass the long-range magnetic forces are dominant over the short range van der Waals forces. In this technique the spatial resolution is ultimately limited by the tip–sample separation (usually between 30–50 nm) [3].

However, this resolution is not sufficient for nanomagnetic devices like spin electronic devices, perpendicular magnetic storage media, and magnetic random access memories [10–12]. In the memories the minimal bit length is expected to be well below 20 nm [13], so improved spatial resolution in MFM technique below 10 nm is clearly needed. Spin-polarized scanning tunneling microscopy [14] and exchange force MFM [15] provide, in principle, surface spin polarization with atomic resolution, but they cannot be used for routine magnetic maps due to high requirements on sample-surface quality and conducting properties of the material under investigation.

Another limitation of current MFM techniques is quantification of magnetic signal. The MFM response is often sufficiently sensitive for qualitative characterization [16,17], but quantitative interpretation of the MFM signal remains a difficult task. MFM images magnetic forces between the tip and the sample, which can be recalculated into magnetic fields in the case when the magnetic field map at the tip apex is known [18]. But, this is not the case for commercial MFM tips [19–21] and the experiments

* Corresponding author.
E-mail address: vladimir.cambel@savba.sk (V. Cambel).

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have shown that the tip calibration is difficult to obtain, and the tip moment is impossible to maintain during scanning.

Force mixing is tightly connected with magnetic invasiveness of the tip, and both problems are primary obstacle to achieve higher spatial resolution. Magnetic forces show exponential decay with increasing tip–sample separation [24]. In order to get satisfactory magnetic field sensitivity for high domain density samples at the lift distance of ~50 nm, one has to use tips with high magnetic moment. But then, huge magnetic fields are generated in tapping mode close to the tip apex (~1 T at ~5–10 nm, [18]), resulting in changes of the original magnetic state of the sample [17,22,23,25–28]. Recently, inverse effect was also reported – the sample has switched the moment direction of the tip [29,30]. On the other hand, if the lift distance is reduced much below ~50 nm and low-moment tips are used, atomic and electric forces are superimposed onto the magnetic-force image and quantitative analysis of the data becomes very difficult.

Here we present an alternative MFM technique, which separates the forces acting on the tip at low tip–sample distances. Switching magnetization MFM (SM-MFM) uses precisely defined low-moment magnetic tips. The technique is based on two scans along the same line using conventional tapping mode, but with alternate tip magnetization in each scan. The method is based on novel magnetic tips with controllable magnetization that can be switched into the opposite direction during the scanning. Below we evaluate the magnetic properties of such MFM tips and find optimal dimensions of the magnetic elements evaporated onto the AFM tip. Theoretical results obtained are further supported by the experiments on Py tip elements.

2. Results and discussion

2.1. SM-MFM tip requirements

The basic principles of SM-MFM [31] are described in Fig. 1. The tip scans the sample twice in conventional tapping mode with tip magnetization orientation reversed between each scan. The two "effective height" traces obtained with opposite in direction and equal in magnitude tip moments are subtracted to obtain a trace of the magnetic force. Obviously, the sum of the traces removes the magnetic interaction and results in "topography" profile.

The magnetic moment of the tip is switched between the two states by applying a low external magnetic field in opposite direction either after each line, or, for stable scanning systems without a drift, after finishing the whole area scan (such systems with external magnetic fields are available on the market). To lower the influence of the external magnetic field on the magnetization state of the sample the switching field amplitude has to be as low as possible.

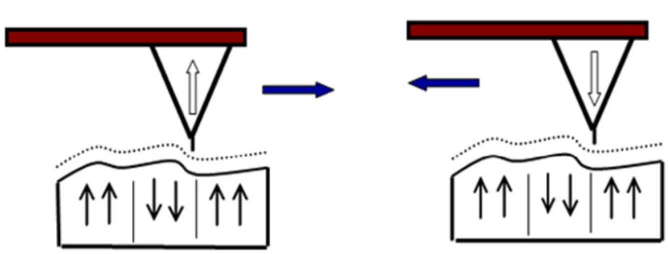

Fig. 1. SM-MFM principle. Both scans done in tapping mode, but the tip magnetization (vertical arrow in the tip) is reversed between them. The addition of the signals gives atomic forces, the difference are magnetic forces.

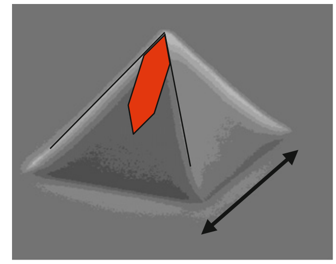

Fig. 2. Side view on a GaAs pyramidal tip. The magnetic element sketched is placed on the tip sidewall close to its apex. External magnetic field in the horizontal direction (black arrow) can reverse the magnetic moment of the element.

Since Py is a soft magnetic material , one has to ensure that the tip moment is not switched by the stray field of the sample [29,30]. Therefore, the external magnetic field should not be switched off during scanning and has to be set slightly above the switching field of the tip.

The spatial resolution of the SM-MFM method is increased as compared to the conventional lift-mode MFM technique due to closer proximity of the tip to the surface. Low magnetization tips can be used in that case due to a small tip–sample distance in tapping mode.

The local magnetization of the tips could be precisely defined by the magnetic element located directly on the tip. SM-MFM tips must show following properties: low magnetic moment, relatively low coercivity for enabling the switching of tip magnetization, and well defined (single) domain state so that magnitude of magnetization remains the same.

Magnetic properties of the SM-MFM tips can be tuned precisely by the shape and thickness of the magnetic element placed on a sidewall of the tip. The element should be located close to the tip apex to achieve high spatial resolution of the SM-MFM technique (Fig. 2). Tips suitable for such magnetic objects are based on sharp GaAs pyramids prepared by wet chemical etching [32]. Using this procedure, 10-μm-high pyramids with smooth sidewalls are fabricated quite easily. We selected pyramids with base angle of 45 degrees. Flat pyramidal sidewalls close to the crystallographic planes of the {1 1 0} type [32,33] are created after etching. Furthermore, non-planar lithography [34] is used to form the Py elements of precise shape on the tip sidewalls close to their apex.

2.2. Micromagnetic calculations of the magnetic properties of SM-MFM tips

We have calculated the magnetic properties of the SM-MFM tip by solving the micromagnetic problem. Main input parameters that have to be optimized include the dimensions (length, width, thickness) and the shape of the Py element located on the tip sidewall close to its apex. The Py element must show low magnetic moment, low switching field, and single-domain state at remanence, and its dimensions are limited by the pyramid sidewalls as discussed previously.

Several groups have studied the magnetic properties of elliptic and rectangular Py elements by the micromagnetic simulations and in experiments. The studies include magnetization processes of square-shaped Py elements under in-plane magnetic fields [35], the magnetization reversal of thin submicron Py ellipses [36], collective effects in arrays of submicron Py ellipses [37] and Py rings [38], the role of edge roughness on magnetization switching in Py nanostructures [39], and the influence of the