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Invited paper

High-resolution magnetic imaging based on scanning probe techniques

U. Hartmann *

Institute of Experimental Physics, University of Saarbrücken, P.O. Box 151150, D-66041 Saarbrücken, Germany

Abstract

Scanning tunneling microscopy (STM) which was invented in 1981, stimulated the development of various scanning probe methods which became important analytical tools in many branches of solid state research. In the meantime, some of the STM offsprings, especially atomic force microscopy (AFM), even became relevant for industrial applications, e.g., for routine sub- μm quality control measurements. Systematic applications of the new techniques in the analysis of magnetic materials started in 1987 with the invention of magnetic force microscopy (MFM). Subsequently spin-polarized scanning tunneling microscopy (SPSTM) and scanning near-field optical microscopy (SNOM) were shown to be at least potentially ultrahigh-resolution magnetic imaging techniques. In the following, a review is given on the state of the art in magnetic imaging by scanning probe microscopies. Special emphasis is put on the capabilities, on still remaining problems and on present trends in the development of further related techniques.

Keywords: Atomic force microscopy; Magnetic imaging techniques; Magnetic force microscopy; Near-field magneto-optical microscopy; Scanning tunneling microscopy

1. Introduction

Scanning probe methods allow the detection of topographic, morphologic, electronic, thermal, mechanical and optical information on a solid surface at the nm scale [1]. Additionally, and this is most important in the present context, various kinds of magnetic information can be achieved at this resolution level. All scanning probe instruments are ultimately based on the same principle, i.e., on scanning a local solid state probe in close proximity across the surface of a sample. The instruments differ only in selectively detecting different kinds of probe-sample interaction from the manifold of interactions which can result between two closely approached solids [2]. In order to detect the desired information, an adequate probe has to be employed. If one is, e.g., interested in the surface atomic-scale electronic structure, the probe has to detect tunneling electrons. If forces represent the interaction of interest, the probe has to be a tiny spring the deflections of which are detected. If surface optical properties are looked for, the probe has to involve a microscopic light transmitter or receiver. All scanning probe techniques are usually operated in the near-field regime of the interaction. Thus, they

inherently have high spatial resolution.

The established magnetic imaging methods either rely on magnetostatic interactions (Bitter technique), on the interaction of electromagnetic waves with the magnetized matter (magneto-optics), or on the interaction of electrons with the sample magnetization or stray field (SEMPA, Lorentz microscopy). The underlying philosophy of the magnetically sensitive scanning probe methods is now simply to scale down macroscopically well-established phenomena to a nm or even to an atomic scale. The possibility of doing so has indeed been demonstrated experimentally for each of the three interaction schemes mentioned above. Magnetostatic interactions are used in the magnetic force microscope (MFM) [3]. Magneto-optics at the nm scale has been demonstrated by scanning near-field optical microscopy (SNOM) [4]. Electronic information on atomic-scale magnetic properties has been achieved by spin-polarized scanning tunneling microscopy (SPSTM) [5]. In the following, each of these scanning probe techniques will be briefly reviewed and some related additional ones will be reported.

2. Magnetic force microscopy

Apart from early tunneling experiments on the detection of flux lines in superconductors [6], and this means in a certain sense on magnetic imaging, MFM was the first scanning probe technique turning out to be a powerful tool

* Fax: +49-681-302-3790; email: ph12uh@rz.uni-sb.de. Also at Institute of Thin Film and Ion Technology, KFA-Jülich, D-52425 Jülich, Germany.

for sub- μm magnetic imaging [7]. The technique is, from the instrumental point of view, very closely related to atomic force microscopy (AFM) [8] and the instruments used are standard or slightly modified scanning force microscopes. In order to achieve local magnetostatic interaction between probe and sample, the microscope's cantilever is equipped with a ferromagnetic tip. Sharp tips are generally obtained in two ways. One can electrochemically etch ferromagnetic wires or single crystals and bend them to produce cantilever and tip. More frequently used are microfabricated Si, SiO_2 or Si_3N_4 cantilevers with monolithically integrated extremely sharp tips which are then covered by a thin ferromagnetic film. Upon raster-scanning the probe at close proximity across the sample surface, the sample's magnetic volume and surface charges lead to a locally varying magnetostatic interaction. This is then detected in the usual way by measuring the deflection of the cantilever in the static mode or its damping in the dynamic mode of MFM operation. 100 nm spatial resolution can be obtained in a routine way, while much better resolution has only occasionally been demonstrated [1].

The biggest advantages of MFM in comparison with other widely used techniques are the following: (1) Since magnetostatic interactions are long-range, MFM is not sensitive to surface contamination. No special sample preparation is generally needed. (2) The technique is non-destructive with respect to the crystallographic structure of the sample. (3) Thin nonmagnetic layers are transparent. By varying the probe-sample distance the sample's topography and magnetic structure can simultaneously be obtained. This especially allows the study of interactions between defects and magnetic properties. (4) MFM can be performed under various environmental conditions. Most important are UHV, liquids, low and elevated temperatures. (5) Samples do not have to be electrically conducting. (6) MFM can be combined with other techniques, preferably with magneto-optical microscopy. Thus, a maximum amount of topographic and magnetic data can be obtained at the same time. Especially (1) has made MFM a widely used technique in the investigation of magnetic data storage media [9]. In basic research the technique is predominantly used to image domain wall configurations and their fine structures. In the literature hundreds of MFM images can be found, so that no standard examples need be presented here. What should, of course, be discussed are the inherent problems being related to the technique.

From the micromagnetic point of view, contrast formation in MFM is based on the interaction of two magnetostatically coupled magnetic multipoles, as schematically shown in Fig. 1. The locally varying magnetization vector field in the sample creates volume charges ρ_s and surface charges σ_s . If one now considers the probe, one almost meets the same situation. Strong surface charges σ_p are created due to the needle-like geometry of the probe, while volume charges ρ_p are located at domain boundaries and crystallographic defects. The first obvious aspect which

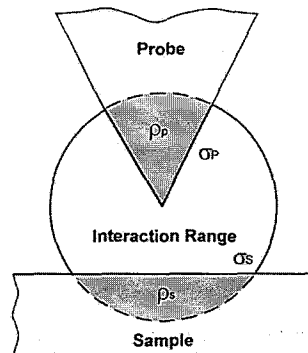


Fig. 1. Probe-sample interaction from the micromagnetic point of view.

results from this point of view is that the MFM image of a given magnetic object strongly depends on the type of probe which is employed, because probes differ in their actual multipole arrangement. This is what one indeed observes in careful experiments. The second problem which immediately results from the consideration of two interacting multipoles is, that the magnetic charges within probe and sample can relax if both are mutually approached. In other words, a minimum-energy state of the micromagnetic system involving probe and sample results in a mutual change of their magnetizations. It has been shown by several theoretical [10,11] as well as experimental [1] investigations that especially the probe can seriously disturb the sample's magnetization. In conclusion, the multipole consideration shows that it is not straightforward to interpret an MFM image. Since MFM is operated in the near-field regime, i.e., at probe-sample distances which are not large compared with the extents of the multipoles in probe and sample, a calculation of the interaction is not simple, and generally involves monopole and dipole terms [2]. Charge relaxation in probe and sample under their mutual influence further complicates contrast formation. These problems can only be overcome if sophisticated magnetic probes become available. The realization of such probes is presently a major subject to MFM research.

It should finally be mentioned that the tunneling-stabilized MFM [12] is a promising alternative to standard MFM from the instrumental point of view. The instrument is essentially an STM equipped with a flexible magnetic tip. The working distance is kept constant by keeping the tunneling current constant. Local magnetic forces which act on the tip appear like corrugations of the sample surface and yield via the STM's feedback loop information on the stray field produced by the sample.

3. Spin-polarized scanning tunneling microscopy

One ultimate goal in magnetic materials research is to understand magnetism at an atomic scale. The basic princi-

ple of SPSTM relies on the fact that the tunneling probability of electrons shows a detectable spin splitting for an appropriate combination of probe and sample materials [13]. Since the STM detects the local variation of the sample's surface density of states near the Fermi level at an atomic scale, SPSTM has obviously the potential for atomic-scale magnetic imaging. In 1990 it was indeed shown that the topological antiferromagnetism of a Cr(001) surface can be verified by STM if a CrO₂ probe is used [5]. Subsequently, further promising results involving real atomic imaging have been obtained on Fe₃O₄(001) surfaces using Fe probes [14].

In SPSTM the main problem is to achieve a sufficiently high spin polarization of the tunneling electrons. The spin polarization is determined by the spin splitting of the electronic density of states in probe and sample at or close to the Fermi level [15]. But even if the splitting is appropriate for some given materials, it is not easy to verify spin-polarized tunneling. The reason is that even weak contaminations of probe and sample generally destroy the spin polarization. Thus, SPSTM a priori requires extremely careful preparation of probes and samples, and the operation under UHV conditions. A very elegant approach to SPSTM was already discussed by Pierce in 1988 [16]. He suggested the use of GaAs as spin-polarized electron source, the electron spin polarization being created by optical excitation with circularly polarized light. Since tunneling of the excited spin-polarized electrons into a magnetic counter electrode is expected to depend on the magnetization of the latter electrode, this can be exploited in a STM to study local surface magnetic structure. Using such a nonmagnetic GaAs probe, interactions with the magnetic sample through long range magnetostatic forces can be excluded. Furthermore, the spin polarization of the GaAs probe can be reversed by optical means offering a convenient way to separate topographic from spin-polarized contributions to the tunneling current. A first big step towards this approach was recently presented [17]. The investigations, however, show that SPSTM utilizing optically pumped semiconductor probes requires further detailed studies on the dependence of photo-induced effects on excitation power, probe-sample distance and doping densities.

4. Scanning near-field magneto-optical microscopy

Magneto-optical microscopy is by far the most widely used imaging technique for magnetic domains. Sophisticated setups and image processing techniques allow the observation of Faraday and Kerr effects, but also a detailed verification of the Voigt and the recently found gradient-related effect [18]. Since everything is, however, based on conventional optics, the observation of magnetic phenomena is diffraction-limited. The use of short-wavelength light sources and higher numerical aperture lenses provide only marginal improvements. Fortunately, the diffraction

limit to resolution in conventional optics is not fundamental but can be circumvented via SNOM [1]. In this technique a subwavelength-sized transmitter or receiver for visible light is placed in close proximity to the sample surface and raster-scanned across the surface to generate an image. In most cases, tapered glass fibers are used as a light source, while the transmitted or reflected light is collected by a conventional objective. Lateral resolutions down to about 10 nm have already been demonstrated.

With respect to applications in magnetic imaging, it was a big breakthrough when it was demonstrated that near-field magneto-optics can be obtained in much the same way as far-field magneto-optics, i.e., simply by using two crossed polarizers [4]. Fig. 2 shows a setup for a near-field magneto-optical microscope which is based on a slightly modified commercial instrument (*Topometrix Aurora*). A probe-sample distance of the order of 10 nm is kept by using shear force control [19]. The light transmitter consists of a small hole (diameter below 100 nm) at the apex of an Al-coated optical fiber. In the transmission as well as in the reflexion mode lateral resolutions well below the optical wavelength have been obtained using an Ar-ion laser with a wavelength of 488 nm. Fig. 3 shows a large-scale overview of the domain wall contrast obtained in the Faraday mode on a 2.69 μm thick YSmBiGaFe garnet film. The same results can be obtained in the Kerr mode. High-resolution cross-sectional scans at domain walls confirm that one reaches at least a lateral resolution of 50 nm on these garnet films. This means that obviously the near-field information is properly transferred to the far-field which is then collected for image processing.

Since, however, SNOM is a rather virginal technique, some basic experimental as well as theoretical questions still have to be answered. Experimental attempts are mainly aimed on further decreasing the size of the light transmitter and on using phase-sensitive techniques for light detection.

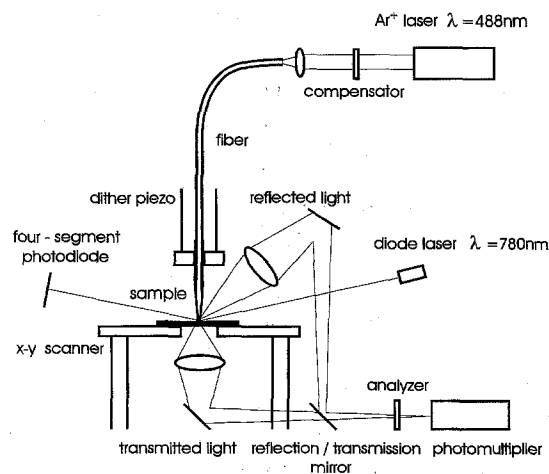


Fig. 2. Realization of a near-field magneto-optical microscope.

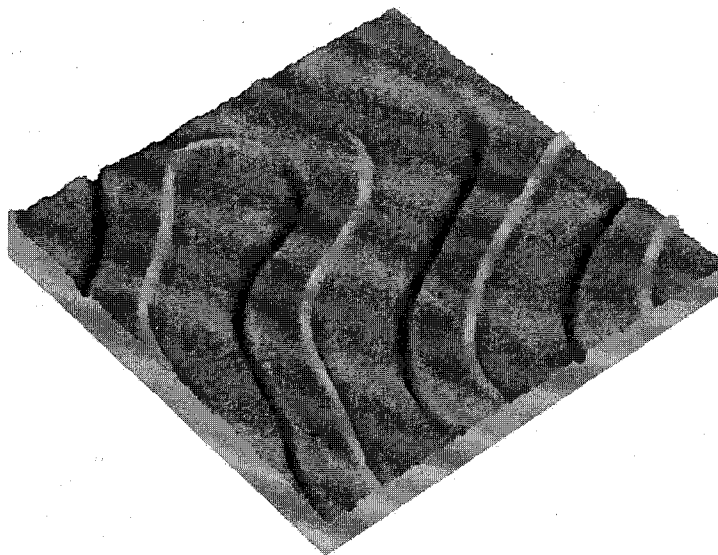


Fig. 3. Faraday-mode domain wall contrast obtained on a garnet sample by near-field magneto-optical microscopy. The scan range is $35\ \mu\text{m} \times 35\ \mu\text{m}$.

Theoretical questions concerning magneto-optical applications of SNOM concentrate on two aspects: It is yet not clear if the dielectric tensor describing the magnetization-induced birefringence of matter is exactly the same as applied for far-field considerations. The second basic question concerns the transference of information from the near-field to the far-field. Apart from these unsolved questions, it is absolutely clear that scanning near-field magneto-optical microscopy will rapidly become one of the most powerful magnetic imaging methods based on scanning probes. The big advantages of this technique especially include the possibility of obtaining magnetic and structural information at the same time and the possibility of not only imaging domains but also writing them.

5. Related techniques

There is certainly no reason to believe that the scanning techniques which have stimulated the development of the discussed offsprings for magnetic imaging will not produce further tools for the sub- μm analysis and modification of magnetic materials. Recent approaches indicate some further promising directions.

Concerning the detection of near-surface magnetic stray fields, the ultimate goal is, of course, to achieve high spatial resolution, a maximum field sensitivity, and quantitatively interpretable data. Fairly high resolution can be obtained by MFM. The field sensitivity is moderate, but up to now no quantitative results have been obtained, e.g., in terms of absolute stray field values. The latter problem has been solved by employing a sub- μm Hall probe [20]. Scanning Hall probe microscopy (SHPM) can be used at low temperatures and exhibits a resolution which is suffi-

cient to image individual flux lines in a superconductor. Another promising technique in this field is certainly advanced scanning SQUID microscopy (SSM) [21], utilizing a force-based distance control. In this way SSM permits the simultaneous detection of topography and magnetic stray field at an unprecedented field sensitivity.

It has already been emphasized that growing attention is being paid to the use of optical interactions for magnetic imaging, utilizing semiconductor probes. Very recently it has been shown that photo-sensitive semiconductor tips employed in a STM can be efficiently used to detect Faraday ellipticity or magnetic circular dichroism [22]. The STM tip is illuminated through a semitransparent magnetic sample by light which is modulated between right- and left-handed circular polarization. The modulated light polarization causes a modulation of the tunneling current between semiconductor tip and magnetic sample. Scanning the probe across the sample at a distance which is controlled by the tunneling current, a varying magnetization leads to a variation of the circular dichroism signal. Using this near-field magneto-optical approach, a lateral resolution of about 250 nm has been demonstrated in magnetic circular dichroism images of bits written in a Pt/Co multilayer. As in the aforementioned techniques, topography and magnetic data are obtained simultaneously.

It seems at the present, that the biggest invention after the discovery of STM and AFM could be spin-resonance force microscopy [23]. Quite some time ago it has been shown that the collective precession of a spin ensemble can be detected in a STM via a modulation of the tunneling current [24]. In spin-resonance force microscopy, spin precession is detected via the induced excitations of the cantilever in a force microscope. The overall setup used

has some similarity to the basic setup known from nuclear, electron or ferromagnetic resonance experiments. The big difference with respect to the conventional setup is, however, that a strong local magnetic field gradient is created by a sharp ferromagnetic tip attached to the cantilever. Upon appropriately tuning in auxiliary rf field, spin resonance is obtained within part of the sample, where the magnetic field produced by the probe locally meets the resonance condition determined by the rf field. The spin precession is magnetostatically coupled to the ferromagnetic probe using appropriate modulation techniques. This results in an excitation of the cantilever at its resonant frequency. Upon raster-scanning the probe across the sample, local variations in the spin-resonance signal are obtained. Additionally the probe-sample separation can be varied, which then varies the vertical position at which resonance is given within the sample. In this way one can look underneath the surface of a sample and obtain some sort of tomographic image. So far, the technique has been demonstrated with sub- μm resolution on paramagnetic samples (ESR). Depending on the employed rf excitation spin-resonance force microscopy should, however, be as well applicable to the detection of nuclear spins (NMR) or ferromagnetic resonance (FR). In order to achieve a high local sensitivity with this very new technique experimental attempts are predominantly aimed on producing soft cantilevers with very high resonant frequency (beyond 1 MHz). Serious theoretical estimations show that it could in principle be possible to detect even one single nuclear spin by spin-resonance force microscopy [25].

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