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A Magnetic Resonance Force Microscope Based on the Solver-HV Probe Complex

E. V. Skorokhodov[a], M. V. Sapozhnikov[a, b], A. N. Reznik[a], V. V. Polyakov[c], V. A. Bykov[c], A. P. Volodin[d], and V. L. Mironov[a, b, *]

[a] *Institute for Physics of Microstructures, Russian Academy of Sciences, Nizhny Novgorod, 603950 Russia*
[b] *Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, 603005 Russia*
[c] *NT-MDT Spectrum Instruments, Zelenograd, Moscow, 124460 Russia*
[d] *KU Leuven, Afdeling Vaste-stoffysica en Magnetisme Celestijnenlaan 200D, BE-3001, Leuven, Belgium*
**e-mail: mironov@ipmras.ru*

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Abstract—The design and operation principles of a magnetic resonance force microscope (MRFM) that has been developed on the basis of the Solver HV vacuum scanning probe microscope are described. This device is intended to study local microwave properties of ferromagnetic micro- and nanostructures in the frequency range of 0.1–20 GHz and in an external magnetic field as high as 0.35 T.

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INTRODUCTION

In recent years, a new method for studying the magnetic properties of microwave nanostructures with a high spatial resolution, that is, magnetic resonance force microscopy, has been intensively developed [1–3]. This method is based on the local detection of high-frequency oscillations of sample magnetization using a sensitive mechanical sensor in the form of an elastic cantilever with a magnetic probe at the end. To increase the sensitivity in magnetic resonance force microscopy, oscillations of the magnetic moments of a sample are excited by a high-frequency field modulated in amplitude at the resonant frequency of the mechanical oscillations of the cantilever. The spectra of magnetic resonance force microscopy are recorded in the form of dependences of the amplitude or phase of the cantilever oscillations on the frequency of microwave pumping or on the external magnetic field.

The principle of detection in magnetic resonance force microscopy of ferromagnetic resonance (FMR) of samples is as follows. The sample magnetization undergoes forced oscillations under the action of an alternating magnetic microwave field, which is modulated in amplitude at the resonance frequency of the cantilever. Under FMR conditions, the amplitude of microwave oscillations of the magnetization increases; thus, the average magnetization of the sample decreases and begins to oscillate at the modulation frequency. These oscillations excite the periodic force acting on the probe, which causes a resonant increase in cantilever oscillations. Far from the FMR, the average magnetization responds weakly to a modulated microwave signal, and swinging of the cantilever does not occur. This detection technique provides a record-breaking sensitivity in recording local magnetic resonances. Images of magnetic resonance force microscopy are recorded at a fixed pumping frequency by scanning the probe above the sample surface. Thus, these images represent the distribution of the amplitude of forced cantilever oscillations as a function of the probe position over the sample and, essentially, the amplitude distribution of the magnetization oscillations over the sample area at a given pumping frequency. The spatial resolution of magnetic resonance force microscopy is determined by the region of magnetostatic interaction of the probe with a sample.

In ferromagnets, due to the strong exchange interaction, absorption of microwave radiation leads to excitation of collective magnetization oscillations, i.e., spin waves. In this case, a magnetic resonance force microscope (MRFM) can be used to study spin-wave resonances. The frequency range of the ferromagnetic resonance for metallic ferromagnets lies in the region above 0.1 GHz. An effective method of controlling the absorption spectrum and spatial modes of spin-wave resonances is the nanostructuring of samples [4–12].

In this paper, we describe the design of a MRFM developed on the basis of a Solver HV vacuum scanning probe microscope serially produced by NT-MDT Spectrum Instruments (Zelenograd, Moscow). This MRFM was developed for recording spectra and spatial amplitude distributions of forced oscillations of

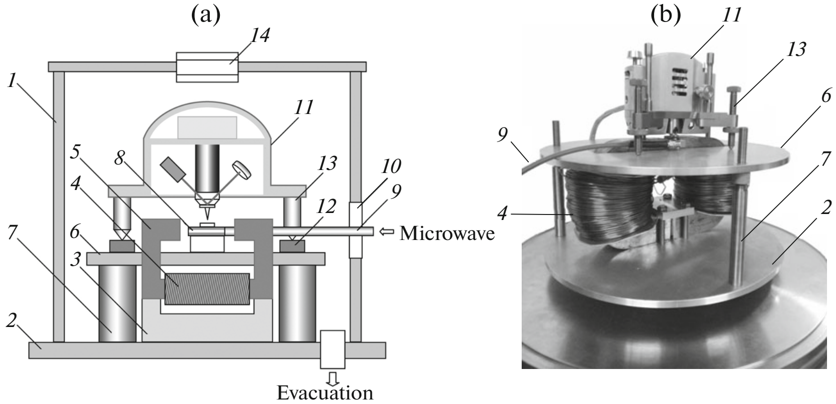

Fig. 1. (a) The diagram of the design and (b) the appearance of the measuring part of the MRFM: (*1*) cylindrical vacuum chamber, (*2*) flange of the vacuum chamber, (*3*) microscope base, (*4*) electromagnet; (*5*) magnetic core, (*6*) platform, (*7*) supports, (*8*) sample holder, (*9*) coaxial cable, (*10*) side flange, (*11*) Smena universal measuring head, (*12*) step motors, (*13*) measuring head supports, and (*14*) glass window for observation.

magnetization in thin-film ferromagnetic nanostructures.

THE MICROSCOPE DESIGN

The diagram of the measuring MRFM part and its coupling to the vacuum chamber are shown in Fig. 1a, while the external appearance of the measuring part is shown in Fig. 1b.

The microscope is located in a cylindrical vacuum chamber *1*. The chamber is pumped out by a turbomolecular pump to a residual pressure of 10^{-5} Torr. The electromagnet *4* is mounted on the base *3* that is located on the lower flange *2* of the vacuum chamber. The electromagnet has a multilayer horseshoe-shaped magnetic core *5* made of transformer iron. The cross section of the magnetic core in the gap between the poles is 30×20 mm^2, and the gap width is 10 mm.

Above the magnet is the platform *6* made of a duralumin sheet. The platform is mounted on three supports *7*, which allow adjustment of its position along the vertical line. The upper plane of the platform is located below the center of the magnet gap. The sample holder *8* is located in the gap of the magnet, which is a short-circuited strip line used for microwave pumping of the sample. The microwave power is supplied to the microstrip line over the coaxial cable *9* through the side flange *10* sealed with vacuum rubber.

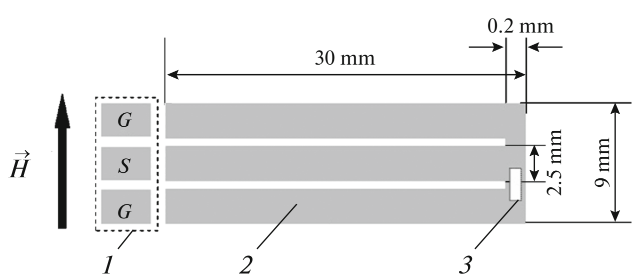

Fig. 2. The diagram of the microstrip line: (*1*) SMA connector, (*2*) shorted strip line, and (*3*) sample. The width of the gap between the strips is 150 μm. The arrow indicates the direction of the external field created by the electromagnet.

The MRFM includes an SFV102NTF/M modified measuring head *11* (NT-MDT Spectrum Instruments), which is made of nonmagnetic materials. A sample is scanned with a probe using a tubular piezoscanner. The maximum scanning area is 100×100 μm. The dynamic range of displacements along the z axis is ± 6 μm. The head is mounted on the platform *6* and can move in the plane of the sample by means of step motors *12* located under the head supports *13*. The range of head movements in the plane is ± 2 mm, while the minimum positioning step is 0.1 μm.

Observation of the MRFM working space is carried out through the glass window *14* in the upper flange of the vacuum chamber with the OPTEM ZOOM 125 long-focus optical system (QIOPTICS, United States) with a video camera and a Sony monitor. The vacuum chamber with a microscope is located on a Halcyonics antivibration platform (HALCYONICS, GmbH, Germany), which provides active suppression of vibrations in the band of 0.6–100 Hz.

A microstrip line made of an RT/duroid 5880 foil-clad plate (ROGERS Co., United States) by optical lithography and chemical etching is used for microwave pumping of samples. The total thickness of the plate is 1.5 mm, the thickness of the copper coating is 17.5 μm, and the dielectric constant is 2.2. The schematic diagram of the microstrip line is shown in Fig. 2.

For matching with the microwave section, the geometric parameters of the line were calculated using a Calculator Microstrip Online specialized software package, which is intended for calculating the impedance of microstrip lines [13].

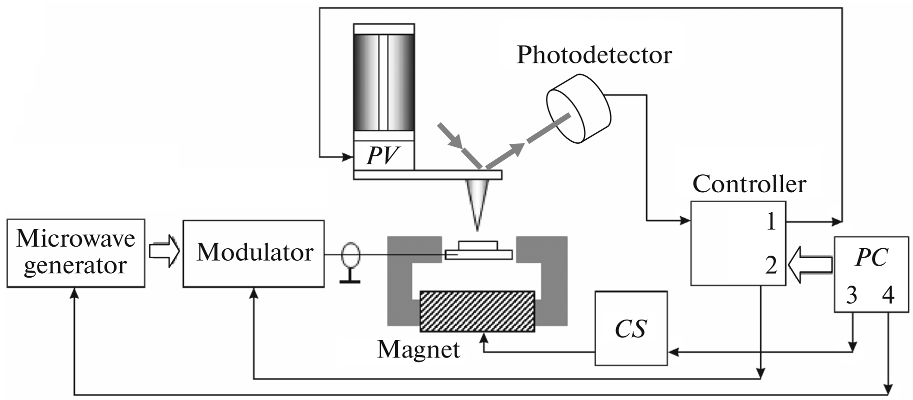

Fig. 3. The functional diagram of the device: (*PV*) piezovibrator, (*CS*) current source, and (*PC*) personal computer.

THE FUNCTIONAL DIAGRAM OF THE MRFM

The functional diagram of the MRFM is shown in Fig. 3. The device is controlled by a BLU-322NTF/M multichannel controller *1* (NT-MDT Spectrum Instruments). The software is a standard control packet of the Nova controller with an additional software add-on that provides the MRFM functions and is developed on the basis of the LabVIEW package. A broadband tunable SPS 20 frequency synthesizer (OOO Spektran, Saratov, Russia) operating in the frequency range of 9 kHz to 20 GHz (the output power is from –10 to +20 dBm) is used for high-speed pumping.

The pumping microwave radiation is modulated in amplitude using a *p*–*i*–*n* diode at a frequency that corresponds to the resonant frequency of the cantilever (the modulation depth is 100%). The modulation frequency is set by a generator built into the controller. The microwave power is applied to the sample using an RG402 coaxial cable with a wave impedance of 50 Ω and a planar microstrip waveguide. The amplitude and phase of the forced oscillations of the cantilever are measured using a synchronous detector at the modulation frequency of the microwave radiation. The microstrip line is fixed in place in the gap of the electromagnet that creates a constant longitudinal magnetic field of up to ±0.35 T. A software-controlled AKIP-1122 current source (ZAO Prist, Moscow) is used as a current source for the electromagnet.

The developed software makes it possible to measure MRFM spectra of samples as dependences of the amplitude and phase of the cantilever oscillations on the microwave pumping frequency f and the external magnetic field H. MRFM images can also be recorded as spatial distributions of the amplitude and phase of the cantilever oscillations at fixed f and H.

THE OPERATION ALGORITHM OF THE MICROSCOPE

The magnetic-resonance force microscope operates according to the following algorithm (see the functional diagram in Fig. 3). The coordinated control of the controller, the microwave generator, and the current source *CS* of the electromagnet is carried out by a personal computer *PC*. First, the spectrum of forced oscillations of the free cantilever is recorded and its resonance frequency f_r and Q factor are determined. To accomplish this, the voltage from the built-in audio-frequency generator of the controller (output 1) is fed to the piezovibrator *PV* of the scanning element and the optical detection system records the dependence of the cantilever oscillation amplitude on the generator frequency. After determining the resonance frequency, the alternating voltage on the piezovibrator is switched off. Then, at the stage of direct measurements, a sinusoidal voltage with an amplitude of 10 V and frequency f_r is supplied from the second generator (output 2) to the modulator. The pumping microwave signal is fed to the second input of the modulator. The modulated microwave signal arrives at the strip line for pumping the sample. The value of the longitudinal magnetic-bias field is set by the *CS* under the computer control (output 3).

Obtaining MRFM spectra imply measurements of either the dependences of the amplitude and phase of cantilever oscillations as functions of the pumping frequency (frequency tuning under the *PC* control, output 4) at a fixed external field, or the dependences of the amplitude and phase on the value of the bias field (field tuning under *PC* control, output 3) at a fixed pumping frequency. An MRFM image of the object under investigation is obtained by scanning the sample in a single-pass mode with a probe at a constant distance between the probe and the sample. In this case, the amplitude and phase of the cantilever oscillations are recorded as functions of the spatial coordinates x and y at fixed values of the bias field and the pumping frequency.

To compensate for the parasitic cantilever oscillations caused by forces of a nonmagnetic nature (caused by the action of modulated microwave radiation), an antiphase voltage (output 1) is applied to the

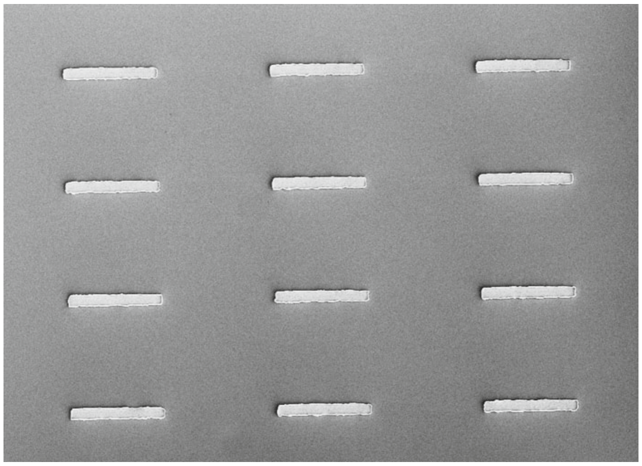

Fig. 4. An image of a portion of an NiFe microstrip array obtained using scanning electron microscopy. The strip dimensions are 3000 × 500 nm.

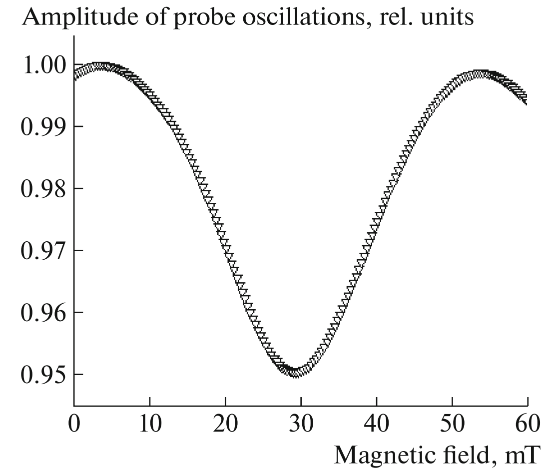

Fig. 5. The MRFM spectrum of the FMR of a NiFe microstrip.

piezoelectric vibrator of the measuring head, which results in suppression of these oscillations.

The sensitivity of the instrument is determined primarily by the probe characteristics; the expression for the minimum detectable force has the form [14]

$$F_{\min} = \sqrt{\frac{2k_{\mathrm{B}}\kappa T\Delta\nu}{\pi Q f_c}},$$

where κ, f_c, and Q are the rigidity, frequency, and quality factor of the cantilever, respectively; T is the temperature, and $\Delta\nu$ is the detection band of the device. In our case, this value is 30 fN.

From the analysis of the signal-to-noise ratio in the detection of the spectrum, we can estimate the sensitivity of the device by a value of 5×10^4 electron spins, which is close (within one order of magnitude) to the thermodynamically determined limit. Further increase in the sensitivity at room temperature is possible due to an increase in the mechanical quality factor of the cantilever used.

The resolution of the microscope is determined by the size of the region of resonant interaction between a sample and the probe and is dependent on the ratio of the FMR line width of the magnetic material to the magnitude of the magnetic field gradient of the probe. For a probe with a magnetic moment oriented in the plane of the sample, the lateral resolution has the form:

$$\delta x = \frac{\Delta H_{\mathrm{res}}}{\partial H_x/\partial z};$$

in our experiments, this is approximately 500 nm.

MRFM INVESTIGATIONS OF PERMALLOY MICROSTRIPS

We conducted test MRFM measurements of the spectra of the FMR array of planar microstrips of permalloy ($Ni_{80}Fe_{20}$; below, NiFe) produced by the lift-off lithography method [15]. The image of the portion of the microstrip array obtained using the scanning electron microscopy is shown in Fig. 4. The strips have dimensions of 3000 × 500 × 30 nm and are arranged on a rectangular lattice with a period of 6 μm in the direction of the long axis and a period of 3.5 μm in the direction of the short axis of the strips.

A standard NSG-1 cantilever (with a resonance frequency of 9.2 kHz and a console hardness of 0.03 N/m) was used as the MRFM sensor, to which a CoSm magnetic particle with a diameter of 10 μm was pasted. The sample was placed on a planar strip line so that the magnetic component of the pumping microwave field was directed along the short axis of the strips. In this case, the external magnetic bias field H was oriented along the long axis of the strips, i.e., perpendicularly to the pumping field. The dependence of the cantilever oscillation amplitude on the external magnetic bias field was recorded. The sample was pumped at frequency f = 5.8 GHz with a power of 20 dBm. The microwave field was modulated in amplitude at the resonance frequency of the cantilever of 9.2 kHz. The measurements were performed in a vacuum of 10^{-3} Torr. The quality factor of the cantilever was 1000.

Measurements in magnetic resonance force microscopy were carried out using a probe in which the magnetic moment was directed along the surface of the sample, in parallel to the long side of the strips. The probe was located above the central region of one of the microstrips at a distance of 3 μm from the surface. An example of the experimental MRFM spec-

Fig. 6. The MRFM image is the image of a section of a microstrip array. The pumping frequency is 5.8 GHz, the bias field is 30 mT, and the distance between the probe and the sample is 1 μm. The dotted lines show the positions of the microstrips. The frame size is 11 × 4 μm.

trum is shown in Fig. 5. A wide dip occurs in the spectrum near the field value of the 30 mT, which corresponds to a quasi-homogeneous FMR in the microstrip [15].

An image of the portion of the microstrip array obtained by magnetic resonance force microscopy is shown in Fig. 6. The experimental parameters were chosen according to the corresponding resonance of the microstrip. The pumping frequency was 5.8 GHz, the magnetic bias field was 30 mT, and the distance between the probe and the sample was 1 μm. The cantilever oscillations caused by the nonmagnetic force of the modulated microwave pumping were compensated by applying an antiphase voltage to the piezoelectric device of the probe holder.

At the selected frequency in a specified magnetic field, the maxima in the MRFM sample image that correspond to the maxima of the cantilever oscillation amplitude are located directly above the central regions of the microstrips.

CONCLUSIONS

In this paper we described the design and operation principles of an MRFM developed on the basis of a Solver-HV vacuum scanning probe microscope. The capabilities of this device were demonstrated based on the example of MRFM investigations of the array of NiFe microstrips. The ability was shown to make local measurements of the FMR spectra, as well as measurements of the spatial distribution of the amplitude of the magnetization oscillations at a preset excitation frequency and the magnitude of the external magnetic field. The proposed MRFM construction essentially expands the functionality of the scanning probe microscope due to the additional ability to investigate the local FMR properties of magnetic microstructures.

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