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Magnetic Resonance Force Microscopy of a Permalloy Microstrip Array

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Abstract—The ferromagnetic resonance in an array of permalloy microstrips 3000 × 500 × 30 nm in size ordered on a rectangular grid 3.5 × 6 μm in size has been investigated by magnetic resonance force microscopy. The dependences of magnetic resonance force microscopy spectra of a sample on the probe–sample distance are analyzed. The possibility of detection of a ferromagnetic resonance spectrum of a single microstrip is demonstrated.

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The microwave properties of thin-film ferromagnetic nanostructures are attracting much attention from researchers as promising candidates for application in planar waveguide-based devices [1–6]. The characteristics of ferromagnetic resonance (FMR) in such systems significantly depend on both the shape and size of individual elements and the spatial architecture of the entire ensemble, as well as on the ways of excitation [7–10]. The method conventionally used for studying the FMR is magnetic resonance spectroscopy based on measurements of microwave radiation absorption by a sample located inside a high-Q resonator in a uniform external magnetic field [11]. This technique, however, requires fabricating large arrays of identical elements, which is a serious technological problem. Recently, a new technique for detecting local microwave properties of materials and nanostructures has been developed, which is called "magnetic resonance force microscopy" (MRFM) and combines the advantages of magnetic force microscopy and resonance microwave diagnostics [12–18]. The main idea of MRFM is detection of a local power interaction between the magnetic force microscope probe and a magnetic sample under microwave pumping. Upon FMR excitation, the static magnetization of a sample changes, which leads to a change in the forces acting on the probe from the side of the sample.

This Letter reports on the MRFM investigations of the FMR in a permalloy microstrip array in a longitudinal magnetizing field. The effect of the probe field on the FMR in individual strips is in focus.

A permalloy ($Ni_{80}Fe_{20}$) microstrip array was fabricated by lift-off lithography. The positive polymethyl methacrylate electron resist layer was deposited onto a silicon substrate with a thickness of 500 μm by centrifuging. An initial mask in the form of an array of rectangular strips was formed in the resist by the electron beam exposure on a SUPRA 50VP microscope with a Carl Zeiss ELPHY PLUS lithography attachment (Jena, Germany). Then, the irradiated resist areas corresponding to the future strips were removed by selective etching in isopropyl alcohol solution of methylisobutyl ketone. After that, a thin (30-nm) permalloy film was deposited onto the sample by magnetron sputtering. The final lift-off process was performed in acetone using ultrasound; as a result, the residual resist layer was removed together with the peralloy film located above it. Thus, an array of ferromagnetic strips 3000 × 500 × 30 nm in size ordered on a rectangular grid with periods of 6 μm in the long strip axis direction and 3.5 μm along the short strip axis was obtained.

The FMR spectra were investigated on a magnetic resonance force microscope fabricated at the Institute for Physics of Microstructures, Russian Academy of Sciences, on the basis of an NT-MDT Solver HV vacuum scanning probe microscope (Zelenograd, Russia). As a probe sensor, we used a standard NSG-1 cantilever with a resonant frequency of 9.2 kHz and a cantilever arm rigidity of 0.03 N/m with a glued SmCo magnet particle 20 μm in size. For microwave pumping of the samples, a tunable Spektran SPS-20 generator (Saratov, Russia) was used. The sample was placed on a planar short-circuited strip line at the microwave magnetic field antinode. The magnetic component of the microwave pump field was directed along the short strip axis. External magnetizing field **H** was induced by a dc electromagnet with a working

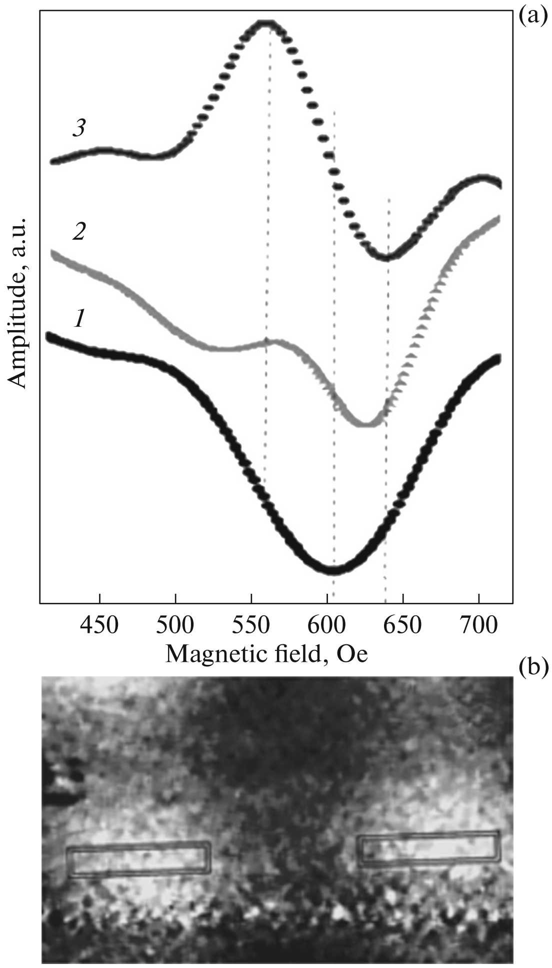

Fig. 1. (a) MRFM spectra of the FMR of NiFe microstrips at probe–sample distances of (*1*) $L = 5$, (*2*) 2, and (*3*) 0.5 μm. The spectra are shifted along the vertical axis for convenience of comparison. (b) MRFM image of part of the microstrip array at a frequency of 5.8 GHz in a magnetizing field of 630 Oe. Contour lines show microstrip positions. The shot size is 10 × 6 μm.

field range of up to 3 kOe and was directed along the strip long axis. The measurements were performed in vacuum under a residual pressure of 10^{-3} mbar. The cantilever mechanical vibration Q factor was 950.

In the experiment, the dependences of the cantilever vibration amplitude on the external magnetizing field were recorded as FMR spectra. The measurements were performed at different distances L between the probe and sample. The sample was pumped at frequency $f = 5.8$ GHz. The pump power was 20 dBm. The microwave field was modulated in amplitude at a modulation depth of 100% at the cantilever resonant frequency. The presence of the modulated microwave field in the microscope working spacing leads to electrostatic attraction (force F_c) between the sample and cantilever [18], which excites cantilever vibrations (the vibrations are induced by a nonmagnetic force). In turn, magnetic force F_m induced between the sample and probe under the FMR conditions depends on the probe position relative to the sample and can be either codirected or oppositely directed with F_c. If the forces F_c and F_m are codirected, the cantilever vibration amplitude under the FMR conditions increases; in the opposite case, it decreases. The experimental MRFM spectra are presented in Fig. 1a.

It can be seen in Fig. 1a that, when the probe is located far above the sample ($L = 5$ μm, curve *1* in Fig. 1a), the spectrum contains a broad dip near a field of 600 Oe. As distance L decreases to 2 μm (curve *2* in Fig. 1a), the resonance field shifts to 625 Oe and a peak at 575 Oe arises. As the probe and sample further approach each other to a distance of $L = 0.5$ μm (curve *3* in Fig. 1a), the positive peak increases and shifts toward a field of 550 Oe and the dip shifts to a field of 630 Oe.

Figure 1b shows an MRFM image of a part of the microstrip array obtained by scanning over the sample. The pump frequency was 5.8 GHz, the magnetizing field was 630 Oe, and the probe–sample distance was 0.5 μm. In this case, the cantilever vibrations induced by a nonmagnetic force were compensated by applying the opposite-phase voltage on a piezoelectric vibrator of the probe sensor holder. It can be seen in Fig. 1b that the FMR areas (the maximum cantilever vibration amplitudes) are located right above the permalloy microstrips.

The observed change in the MRFM spectrum is related to the effect of the probe field on the microstrip resonance. The expression for the force of interaction between the probe and sample, which causes the probe vibrations, can be written as

$$\mathbf{F} = -\nabla \int_{V_{\text{sample}}} (\mathbf{m} \cdot \mathbf{h}_p) dV, \tag{1}$$

where $\mathbf{m}$ is the quasi-static sample magnetization component, which oscillates at the frequency equal to the cantilever resonant frequency under microwave pumping [15–18], and $\mathbf{h}_p$ is the probe magnetic field. The cantilever is built up by the z component of the force

$$F_z = -\int_{V_{\text{sample}}} m_x \frac{\partial h_{px}}{\partial z} dV \tag{2}$$

with the sign determined by the sign of the derivative

$$h'_{px} = \frac{\partial h_{px}}{\partial z}. \tag{3}$$

In the simplest model corresponding to the experiment, the probe can be presented in the form of a sphere [19] uniformly magnetized along the x axis (Fig. 2).

In this case, the space above the sample is divided in several parts (A and B in Fig. 2) with different signs of the longitudinal components of the probe field h_{px} and field gradient h'_{px}. The magnetic-field x-component sign changes at the boundary (dashed line in Fig. 2) determined by the condition

$$x = \pm\frac{z}{\sqrt{2}}. \tag{4}$$

In this case, the apex angle of the area between the dash-and-dot lines is 71°. The magnetic-field gradient sign changes at the boundary shown by the dash-and-dot line in Fig. 2 and determined by the condition

$$x = \pm\frac{z}{2}. \tag{5}$$

The apex angle of the area between the dashed lines is 54° (Fig. 2).

The probe magnetic field acts on the sample and changes the FMR conditions. Indeed, the resonant frequency of the fundamental mode of the vibrations of magnetization of a ferromagnetic microstrip can be estimated using the Kittel formula [20, 21]

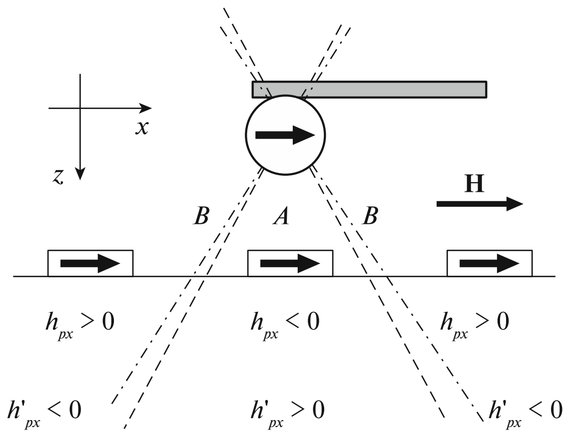

Fig. 2. Probe magnetic-field structure above the microstrip array. Dash-and-dot lines show the cross section of conical areas with different projections of the probe field h_{px} and dashed lines show the areas with different signs of the gradient h'_{px}.

$$f = \frac{\gamma}{2\pi}\sqrt{((H_x + h_{px}) + (N_{zz} - N_{xx})M_s)((H_x + h_{px}) + (N_{yy} - N_{xx})M_s)}, \tag{6}$$

where N_{xx}, N_{yy}, and N_{zz} are the main values of the tensor of strip demagnetizing factors, M_s is the permalloy saturation magnetization, and γ is the gyromagnetic ratio. H_x and h_{px} are the projections of the external magnetizing field and probe magnetic field onto the x axis, respectively (directed along the long strip side). It can be seen from (6) that the probe field leads to the strip resonant frequency shift with the sign determined by the sign of the h_{px} longitudinal component. Therefore, according to the spatial structure of the probe field, the resonant frequency of the strips located in areas B increases and, consequently, the resonance field decreases, since $h_{px} > 0$, while the resonant frequency of the strips inside area A decreases and, consequently, the resonance field increases, since $h_{px} < 0$. In addition, the gradients h'_{px} also have different signs in areas A and B. The direction of the magnetic force between the sample and cantilever changes correspondingly. The interaction of the probe with the strips located in areas B makes a positive contribution to the build-up force and leads to an increase in the cantilever-vibration amplitude; the interaction with the strips located in area A makes a negative contribution and leads to a decrease in the vibration amplitude.

At large distances L, the probe interacts simultaneously with several strips under different resonance conditions, which leads to the formation of a broad resonance peak (curve *1* in Fig. 1a). As the distance L decreases, the number of strips that hit area A decreases and, at a distance of L = 0.5 μm, only one strip yielding a peak with a resonance field of 630 Oe appears in area A. The remaining neighboring strips appear in area B and create a positive response with a resonance field of 550 Oe.

Thus, we have studied the ferromagnetic resonance of the array of permalloy microstrips by magnetic resonance force microscopy. It was shown that the structure of FMR spectra significantly depends on the distance between the probe and sample. At a distance of 5 μm, one dip is observed, which is formed by several permalloy strips. As the distance decreases, two resonance peaks form, one of which is positive and the other is negative. These resonance responses are related to two groups of particles, one lying in the area with the positive probe magnetic-field gradient and the other in the area with the negative probe magnetic-field gradient. At small probe–sample distances, we managed to detect FMR of a single strip.

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REFERENCES

1. I. Žutić, J. Fabian, and S. Das Sarma, Rev. Mod. Phys. **76**, 323 (2004).

2. V. E. Demidov, S. O. Demokritov, K. Rott, P. Krzysteczko, and G. Reiss, Appl. Phys. Lett. **92**, 232503 (2008).
3. M. Krawczyk and D. Grundler, J. Phys.: Condens. Matter **26**, 123202 (2014).
4. G. Duerr, K. Thurner, J. Topp, R. Huber, and D. Grundler, Phys. Rev. Lett. **108**, 227202 (2012).
5. S. Tacchi, B. Botters, M. Madami, J. W. Kłos, M. L. Sokolovskyy, M. Krawczyk, G. Gubbiotti, G. Carlotti, A. O. Adeyeye, S. Neusser, and D. Grundler, Phys. Rev. B **86**, 014417 (2012).
6. V. L. Zhang, H. S. Lim, C. S. Lin, Z. K. Wang, S. C. Ng, M. H. Kuok, S. Jain, A. O. Adeyeye, and M. G. Cottam, Appl. Phys. Lett. **99**, 143118 (2011).
7. S. Jain, M. Kostylev, and A. O. Adeyeye, Phys. Rev. B **82**, 214422 (2010).
8. R. V. Gorev, E. V. Skorokhodov, and V. L. Mironov, Phys. Solid State **58**, 2212 (2016).
9. E. V. Skorohodov, R. V. Gorev, R. R. Yakubov, E. S. Demidov, Yu. V. Khivintsev, Yu. A. Filimonov, and V. L. Mironov, J. Magn. Magn. Mater. **424**, 118 (2017).
10. M. V. Sapozhnikov, L. I. Budarin, and E. S. Demidov, J. Magn. Magn. Mater. **449**, 68 (2018).
11. I. Wertz and J. Bolton, *Electron Spin Resonance* (McGraw-Hill, New York, 1972).
12. D. Rugar, C. S. Yannoni, and J. A. Sidles, Nature (London, U.K.) **360**, 563 (1992).
13. O. Züger and D. Rugar, Appl. Phys. Lett. **63**, 2496 (1993).
14. Z. Zhang, P. C. Hammel, and P. E. Wigen, Appl. Phys. Lett. **68**, 2005 (1996).
15. H.-J. Chia, F. Guo, L. M. Belova, and D. McMichael, Phys. Rev. B **86**, 184406 (2012).
16. F. Guo, L. M. Belova, and D. McMichael, Phys. Rev. Lett. **110**, 017601 (2013).
17. Yu. Obukhov, D. V. Pelekhov, J. Kim, P. Banerjee, I. Martin, E. Nazaretski, R. Movshovich, S. An, T. J. Gramila, S. Batra, and P. C. Hammel, Phys. Rev. Lett. **100**, 197601 (2008).
18. O. Klein, G. de Loubens, V. V. Naletov, F. Boust, T. Guillet, H. Hurdequint, A. Leksikov, A. N. Slavin, V. S. Tiberkevich, and N. Vukadinovic, Phys. Rev. B **78**, 144410 (2008).
19. V. L. Mironov, A. A. Fraerman, B. A. Gribkov, O. L. Ermolayeva, A. Yu. Klimov, S. A. Gusev, I. M. Nefedov, and I. A. Shereshevskii, Phys. Met. Metallogr. **110**, 708 (2010).
20. V. A. Bokov, *Physics of Magnet* (Nevskii Dialekt, St. Petersburg, 2002) [in Russian].
21. A. G. Gurevich and G. A. Melkov, *Magnetization Oscillations and Waves* (Fizmatlit, Moscow, 1994; CRC, Boca Raton, FL, 1996).

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