Specific Features of Observing Magnetization Inhomogeneities on the Surface of Permalloy Thin Films by Means of Highly Sensitive Magnetic-Force-Microscopy Probes

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Abstract—The results of studying regions of inhomogeneous magnetization on the surface of permalloy thin films with the use of fabricated highly sensitive probes of magnetic force microscopy (MFM) are presented. The technological features of manufacturing MFM probes with a high sensitivity to magnetic-field gradient are analyzed. Regions of ordering of the vertical component of the magnetic field are revealed, and domain walls are visualized in the thin films under study. Nanoscale measurements of the domain-wall thicknesses are performed.

Keywords: magnetic-force microscopy, permalloy thin films, domain walls

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INTRODUCTION

The invention of precision alloy FeNi (permalloy) by Gustav Elmen in 1914 opened up a new phase in studying ferromagnetic alloys with soft magnetic properties. Along with the expansion of fields of permalloy application as a material for magnetic-recording heads, magnetic-field sensors, protective coating for shielding against the magnetic field of magnetic-resonance tomography systems, electron microscopes, and integrated circuits, the interest of researchers around the world has proportionally increased in the most comprehensive and highest-quality investigation of the magnetic nature of this new material and, in particular, the domain structure of both permalloy thin films and micro- and nanoscale particles of the material under study [1].

The most studied and common method for investigating the structures of ferromagnetic domains and regions of spontaneous magnetization, in an external magnetic field, in vacuum, at an elevated or lowered temperature, and in the absence of the impact of additional external factors, is magnetic-force microscopy (MFM). Being an effective means for studying magnetic structures in the micrometer, submicrometer, and nanoscale ranges, MFM yields a high-quality result of the distribution of the vertical component of magnetic field over the surface of a sample [2]. The image obtained using MFM is the spatial distribution of a certain parameter (in this case, the phase shift of cantilever vibrations) characterizing the probe—sample magnetic interaction. The cantilever with a magnetic probe used in the studies is a modernized silicon cantilever whose specific feature is a coating made of some magnetic material of nanoscale thickness. The MFM measurements allow magnetic domain structures to be studied with high spatial resolution and superior sensitivity. In turn, the high aspect ratio of the probe tip is responsible in the majority of cases for the quality of the spatial resolution of both the surface relief and the magnetic image.

FABRICATION OF MFM CANTILEVERS

To achieve the highest-quality result in studying nanoscale magnetic inhomogeneities in thin films of ferromagnetic structures in the absence of an external magnetic field, it is necessary to use cantilevers with a probe curvature radius of no more than 25 nm. The magnetic cantilevers used in our work which satisfied this requirement were fabricated at the Nano- and Microsystem Technology Scientific-Technological Center of the MIET National Research University of Electronic Technology. The samples of permalloy films were fabricated at the same center.

The silicon cantilevers with a high aspect ratio of the conical needle having a tip size of no more than 10 nm were manufactured using the technology of micro-electro-mechanical systems (MEMS), which was designed for microelectronics production. A magnetic coating was applied by the slow magnetron sputtering of a target of cobalt—chromium alloy (CoCr) with a thickness of 5–7 nm onto the silicon cantilever.
Frequently magnetic cantilevers lose their magnetic properties rather fast due to surface corrosion and subsequent degradation of the magnetic properties, therefore some of the fabricated cantilevers were coated with a thin (5 nm) film of \( \text{Al}_2\text{O}_3 \). For ordering the magnetic-moment direction in the probe-tip material, the probes manufactured and prepared for work were kept for an hour in a vertically oriented magnetic field; the value of the magnetic-field induction was 2 T.

According to the results of technological works carried out, magnetic probes were fabricated which were coated with a thin film of cobalt—chromium alloy with a thickness of about 5 nm, and a curvature radius of the probe tip of no more than 25 nm (Fig. 1).

**EXPERIMENTAL TECHNIQUE**

During magnetic studies at the submicrometer level, it is necessary above all to separate the “magnetic” images from the relief images. To solve this problem, magnetic measurements were taken according to the two-pass technique. The technique of dynamic MFM was used: in the first pass, the surface relief was determined using the semi-contact method, which is the standard method for a scanning probe microscope. In the second pass, a cantilever vibrating at the resonance frequency was used to detect the magnetic field. Using a feedback system, the distance between the scanned surface and fixed cantilever tip was maintained constant in the second pass; scanning proceeded in accordance with the relief recorded in the first pass. The probe—surface distance should be large enough for Van der Waals forces to be disregarded and for the cantilever to be exposed only to the long-range magnetic force. According to this method, both the relief image and the magnetic image can be obtained sequentially for the same surface part.

**EXPERIMENTAL**

The fundamental possibility of studying the structures of domain walls of ferromagnetic thin films under exposure to an external magnetic field was demonstrated in [3]. An attempt to explain the direction of the magnetization vector of FeNi-based thin-film...