Defense Technical Information Center Compilation Part Notice

ADP012828

TITLE: Micromagnetic Properties and Magnetization Reversal of Ni Nanoparticles Studied by Magnetic Force Microscopy

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Hard copy only.

This paper is part of the following report:

TITLE: Nanostructures: Physics and Technology International Symposium [6th] held in St. Petersburg, Russia on June 22-26, 1998 Proceedings

To order the complete compilation report, use: ADA406591

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP012712 thru ADP012852

Ioffe Institute **NC.05**
6th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 22–26, 1998.

Micromagnetic properties and magnetization reversal of Ni nanoparticles studied by magnetic force microscopy

A. A. Bukharaev†, D. V. Ovchinnikov†, N. I. Nurgazizov†, E. F. Kukovitskii†, M. S. Kleiber‡ and R. Wiesendanger‡

† Kazan Physical Technical Institute Russian Academy of Sciences, Sibirsky Tract, 10/7, Kazan, 420029, Russian Federation

‡ Institute of Applied Physics,Jungiusstrasse 11, 20355, Hamburg, Germany

Abstract. Ni nanoparticles with sizes ranging from 40 to 400 nm formed by thermal annealing of thin film were investigated by atomic and magnetic force microscopy *in situ* in presence of applied magnetic field up to 300 Oe. By comparison of the corresponding experimental AFM and MFM images and computer simulated MFM images, the small particles with diameter below 100 nm were found to be in single domain state. The the direction of total magnetization of greater particles is defined by their shape anisotropy. The MFM image features and the magnetization reversal mechanism of such particles are explained in terms of a vortex magnetization.

Introduction

Scanning probe microscopy permits simultaneous measurements of the topography and magnetic stray field of the sample with nanometer-scale resolution [1]. It is essential, that it is possible to study magnetization reversal of surface structures with magnetic force microscopy (MFM) *in situ* using an external magnetic field [2]. A special interest at the present time is caused by planar magnetic nanostructures, containing isolated ferromagnetic single domain nanoparticles because of their potential as ultra high density magnetic storage media (so-called quantized magnetic disks—QMD [3]).

The detection of uniformly magnetized ferromagnetic nanoparticles obtained after thermal annealing of the thin nickel film with MFM and the studying of the dependence of magnetization reversal process in such particles on their shapes and sizes in the presence of applied magnetic field are the purposes of the present work.

Experiments and discussion

Surface topography images with nanometer-scale resolution were obtained with scanning probe microscope P4-SPM-MDT. Magnetic measurements were taken by Nanoscope III. In both microscopes a.c. mode was used. Working in lift mode with double scanning of each line with registrating at first a relief and then magnetic interaction allows to obtain simultaneously the topographical and magnetic image of the same place of a surface. The resulting magnetic image consists of dark and light sites (so-called magnetic contrast), corresponding to areas with various magnetic interaction of a magnetic tip with a surface [1].

The Si cantilevers coated by Fe were used during magnetic measurements. Previously the tip was magnetized so that its magnetization direction was perpendicular to the sample surface. During the experiments on magnetization reversal *in situ* the MFM was placed between electromagnet poles so as external magnetic field ranged from −300 up to +300 Oe was along the surface plane.

The Ni films were prepared on fused quartz substrates with vacuum evaporation. The AFM images show that such film consists of the tightly adjoining Ni islands completely covering the substrate, with their profile heights ranging from 30 up to 70 nm. In other words, the metal islands are connected to themselves by bridges.

After annealing in atmosphere at 800°C well separated particles mainly of two types were obtained: small with diameter from 60 up to 150 nm and height up to 65 nm (Fig. 1*a*), and greater with diameter from 250 up to 400 nm and height up to 250 nm. Majority of particles with the lateral sizes less then 150 nm have the shape close to spherical, however, among the greater particles there are the axial particles with the aspect ratio 1:2 (more rarely 1:3). From measurements on boundary of film-substrate it is well visible that the particles are placed separately and do not touch each other. The AFM data shows, that during the annealing the bridges between metal islands tear because the metal islands tend to have the thermodynamically equilibrium shape, defined by forces of surface tension, at high temperature. The observable film transformation is known as a self-coalescence process [4].

Visible lateral sizes of the small particles, with radius comparable to tip radius, can be essential larger than true ones due to known tip-sample convolution effect. Therefore earlier offered numerical deconvolution technique was used for estimating of the lateral sizes of particles [5]. The corrected diameters of particles with the visible lateral sizes less than 150 nm were approximately on 30 percents less owing to convolution with such tip. The small particles with heights up to 70 nm had nearly spherical shape, as their real diameters were equal to 80–90 nm.

The known formula for magnetic interactions [1] have been used for computer simulation of the MFM images from the Ni particles. A particle was approximated by the cylinder, height and diameter of which coincide with the sizes of the particle. The cylinder was divided into 900 fragments. Each fragment was substituted by a single magnetic dipole, which was placed in a barycentre of the fragment. In single domain state when the magnetic moments of all fragments of the particle are oriented uniformly along the surface the corresponding magnetic image should have characteristic view, presented in Fig. 1*b*. The magnetic contrast (dark and light areas on the MFM image) is connected with formation of magnetic poles on the ends of single-domain ferromagnetic particle. The line which connects centers of light and dark areas on the magnetic image shows the direction of vector of summarized particle magnetization (**M**).

In case of absence of an additional external field, the MFM images with enough strong magnetic contrast which is characteristic to uniform magnetization, were observed only from rather small spherical particles, with a visible diameter less than 100 nm that is well conformed to known theoretical and experimental value of the critical size of a single domain state for Ni particles, which is equal to 60 nm [6]. The magnetization of axial ones was directed along a long axis of the particle, that is along an easy axis of magnetization.

Under rather small external magnetic field (300 Oe) all magnetic moments of Ni spherical particles line up along the field with saving a high degree of an order (Fig. 1*c*). After change of direction of the external magnetic field on 180° magnetization vector **M** of the particle also turns on 180° (Fig. 1*d*), that is characteristic of magnetic reversal

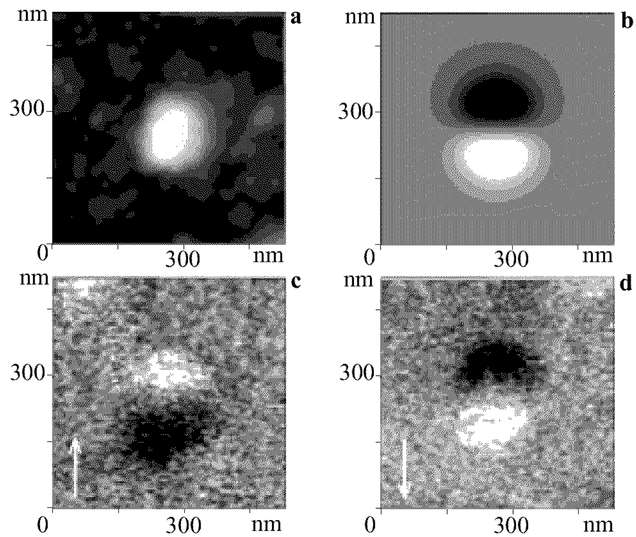

Fig 1. Magnetization reversal of single domain Ni particle in an external magnetic field. *a*—topographic image of the particle; *b*—computer simulation of MFM-image, corresponding to this particle. *c, d*—experimental MFM-image of the same particle at the presence of field 300 Oe (direction of the field is marked by the arrows).

of single domain particles [2].

The magnetic contrast from lager particles is much weaker and has more complex structure. It testifies that such particles are not single domain and are magnetized non-uniformly. The experimental magnetic images of these particles do not show domain walls. It allows to assume, that vortex distribution of magnetization is characteristic for the larger particles. The presence of magnetization turbulences in a particle should considerably reduce the magnitude of magnetic interaction of a microprobe with such particle and also reduce magnetic contrast.

The process of magnetic reversal of larger particles differs from magnetic reversal of single domain particles. The switching on of an additional external field (300 Oe) during measurements appreciably strengthens magnetic contrast, first of all for axial particles with magnetization directed along the field or under a small angle to it, what speaks about increase of a degree of uniformity of their magnetization. It is essential, that the direction of a vector of a total magnetization **M** for axial particles does not coincide with an external field and builds along a long axis of the particle, that coincides with an axis of easy magnetization of the particle connected to its shape anisotropy. The features of magnetic reversal of axial particles, apparently, are connected to their individual hysteresis properties, that is to influence of such factors as its shape anisotropy, magnetic crystalline anisotropy, remanent magnetization, external field magnitude on a degree of magnetic order of separate particle. The assumption of non-uniform magnetic reversal of large particles with formation of vortex structures is well enough coordinated with experimental researches and theoretical accounts carried out earlier by other methods [7].

Thus, in the work the first results demonstrating successful applying of atomic and magnetic force microscopy for study of morphology, micromagnetism and magnetization reversal of Ni nanoparticles obtained by coalescence method are submitted. The isolated metal particles with the lateral sizes from 40 up to 400 nm and height from 40 up to 250 nm were fabricated on the surface of fused quartz. The particles with size less than 100 nm had the shape close to spherical. The larger flat particles were both round, and axial with aspect ratio 1:2 mainly. By comparison of the corresponding topographical and magnetic images, and also with computer simulation of the magnetic images it was found, that the particles with size less than 100 nm are single domain and easily switch in a direction of an external field, keeping a uniform magnetization. The increase of a degree of uniformity of magnetization in magnetic field is characteristic for larger axial particles, however, the direction of total magnetization of such particles is defined by an anisotropy of their shape, instead of external field. The features of the magnetic images of particles with the size more than 150 nm and mechanisms of their magnetization reversal is associated with the presence of vortex structure of magnetization in them.

The work is supported by Program "Physics of solid state nanostructures" (Grant 96-1034), by Russian Basic Research Foundation (Grant 96-02-16323) and by Russian Ministry of Sciences and Technologies (Grant 143/57/4).

References

[1] Grutter P., Mamin H. J. and Rugar D. *Magnetic Force Microscopy (MFM): Scanning Tunneling Microscopy. II.*, Berlin: Springer Verlag, 1992.
[2] Lohndorf M., Wadas A., Lutjering G., Weiss D., Weisendanger R. *Z. Phys. B* **101** 1 (1996).
[3] Chou S. Y., Kraus P. R., Kong L. *J. Appl. Phys.* **79** 6101 (1996).
[4] Trusov L. I., Holmyansky V. A. *Island Metal Films*, Moscow: Metallurgiya, 1973.
[5] Bukharaev A. A., Berdunov N. V., Ovchinnikov D. V., Salikhov K. M. *Microelectronics.* **26** 163 (1997).
[6] Kondorsky E. I. *Izvestya of AS USSR. Physical series.* **42** 1638 (1978).
[7] Fredkin D. R., Koehler T. R. *J. Appl. Phys.* **67** 5544 (1990).