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Citation: Journal of Applied Physics **99**, 08B707 (2006); doi: 10.1063/1.2172888
View online: http://dx.doi.org/10.1063/1.2172888
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/99/8?ver=pdfcov
Published by the AIP Publishing

Detection of the domain structure change using magnetotransport for a series of circular Permalloy dots

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(Presented on 2 November 2005; published online 25 April 2006)

The magnetic structure of a magnetic dot depends on its geometrical factors such as thickness and dot size and can be either a multidomain state or a vortex state. The magnetoresistance (MR) of a series of magnetic dots with diameters ranging from 0.3 to 5 μm was measured to investigate the correlation between domain-structure and magnetotransport properties. A dot with a diameter of less than 2 μm has a domain of vortex state at remanence and demonstrates similar reversible MR results. Moreover, the behaviors of MR show clear changes corresponding to the domain-structure change from vortex to multidomain states with an increasing dot diameter. Data can be qualitatively described by the anisotropic magnetoresistive effect. Hence, our results show that the magnetotransport can be a tool to detect the magnetic domain structure of a submicron magnetic dot. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2172888]

I. INTRODUCTION

Recent advances in the nanofabrication methods have made the possibility of studying the magnetism at a small length scale, in which can be potential applications in high density recording and modern magnetoelectronic devices. The magnetic reversal process in circular,[1] square,[2] or other shape dots[3] has been studied for a while by μ-MOKE,[1–4] magnetic force microscopy (MFM),[4–6] scanning tunneling microscopy (STM),[7] Lorentz microscopy,[8] and electron holography.[9] For circular dots of soft magnetic material, it has been found that the short range exchange energy is more important than the long range magnetostatic energy in determining the magnetization configurations when the dimension is decreased. Between the multidomain and single-domain states the flux closure state is generated during the reversal process and is called the vortex state. From the practical viewpoint, the studies of magnetoresistance (MR) are very important. Transport phenomena may occur for structures in sufficiently reduced dimensions. Up to now, almost all MR studies in nanostructures are focused on nanowires[10] and rings.[11] The MR study of a single dot is very rare due to the probing difficulty. Recently, Vavassori *et al.*[12] reported the MR measurement in a circular Permalloy dot with a diameter of 1 μm and a thickness of 25 nm. In their device, four 10 nm Au leads were arranged underneath the dot at four corners for electrical contacts resulting in a nonuniform current distribution and uncertain dot domain reversal processes. Here we used a simple design of electric contact configuration to obtain MR of a single submicron magnetic dot. In this work, the MR of a series of different size Permalloy dots was measured to investigate the correlation between domain-structure and magnetotransport properties.

II. EXPERIMENTAL DETAILS

Our samples were prepared by standard e-beam lithography, thermal evaporation, and lift-off techniques. The circular Permalloy dots have a thickness of 45 nm and diameters of 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 2, and 5 μm, respectively. In order to make an electrical measurement, several identical dots were distributed evenly atop a 30 nm thick Au strip with a width same as the diameter of the dots. Contact configuration was arranged for a four-terminal electrical measurement. Figure 1 shows a scanning electron microscopy image of one of our samples. A device contains numerous areas of different dot sizes. The image exhibits that the dots keep a completely disklike shape and the separation between the neighboring dots in each area is about the same as the dot diameter.

Magnetic structure and magnetotransport measurements were performed. The former was obtained using a magnetic force microscope (Nanoscope Dimension 3100) in the tapping/lift mode. The magnetic configurations were imaged at a lift height of 100 nm by commercial CoCr coated Si cantilever tips. The latter was performed in a pumped ^{4}He cryostat and at the center of a superconducting magnet solenoid. For the electrical measurement, several dots in series were used to increase the signal to noise ratio instead of a single dot. Single dot behavior can be extracted simply by using Kirchhoff's circuit theorem. A chain of N dots can be treated as N+1 Au square sheets (dot spacing) in series with N combinative resistors of a dot and Au sheet in parallel. An independent experiment of a sequence of N confirmed such circuit analysis.[13] Hence, electrical transport of a single dot is easily obtained using such contact configuration.

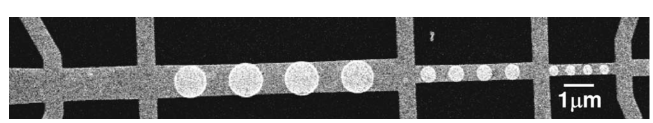

FIG. 1. Scanning electron microscopy (SEM) image of one sample. Measuring current is applied along the long Au strip and resistance is measured between two neighboring vertical Au contacts. In this device, four sections are arranged for studies of bare Au and Permalloy dots with diameters of 1, 0.6, and 0.3 μm (from left to right).

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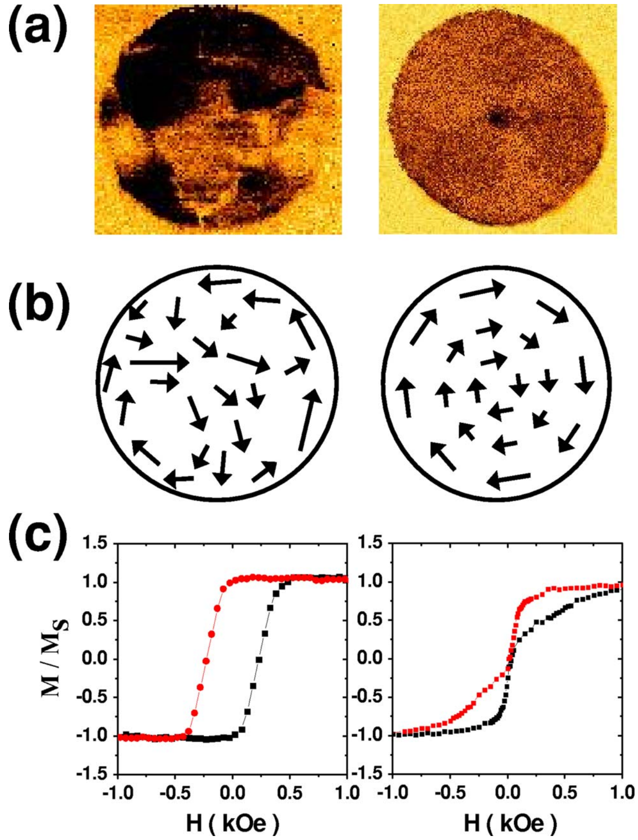

FIG. 2. (a) MFM images of two dots with diameters of 5 (left) and 0.8 μm (right), respectively. (b) The arrow line sketches to show two domain structures in (a). (c) Normalized magnetization moments as a function of applied field H of two dot arrays with diameters of 5 (left) and 0.8 (right) μm.

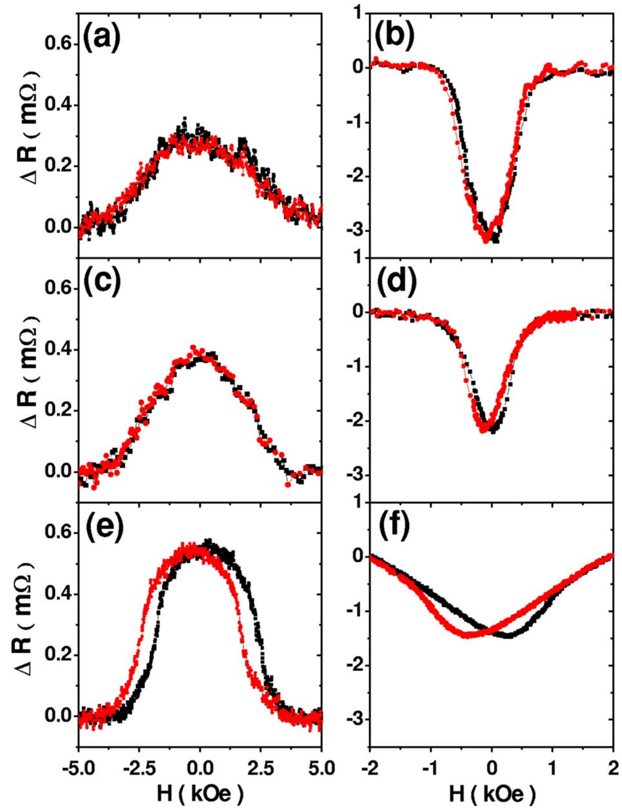

FIG. 3. The MR behaviors of three different diameter Permalloy dots. 0.6 [(a) and (b)], 1 [(c) and (d)], and 5 μm [(e) and (f)], respectively, at T =5 K. The left figures [(a), (c), and (e)] are $\Delta R_\perp$ where the field is perpendicular to the film plane and the right figures [(b), (d), and (f)] are $\Delta R_\parallel$ where the field is parallel to both film plane and measuring current.

III. EXPERIMENTAL RESULTS AND DISCUSSION

It has been known that the magnetic structure of a magnetic dot depends on its geometrical factors such as thickness and dot size. To check the magnetization state of our 45 nm thick Permalloy dots we investigated the domain structure using MFM at room temperature. Figure 2(a) shows the MFM images of two samples with diameters of 5 and 0.8 μm, respectively, at remanence. Prior to image scanning, dots were magnetized in an opposite out-of-plane field to prevent magnetic configuration of the dots from being distorted by the stray field of the tip.[6] As seen from Fig. 2(a), a contrast spot is at the center for a 0.8 μm dot corresponding to the turned-down vortex core, while a complicated combination of dark and bright areas is present for a 5 μm dot. In Fig. 2(b) the arrow lines for local spin are sketched to show the difference between these two domain structures. These results can also be confirmed by the magnetic moment behaviors. Corresponding MH curves of the same size dot arrays are plotted in Fig. 2(c). The sudden loss of magnetization close to zero field for the smaller dot array is very characteristic of the formation of the vortex state. MFM and magnetization moment investigations show that dots with a diameter of less than 2 μm are in the vortex states and a dot with a diameter of 5 μm is in multidomain state, at remanence.

Before discussing the magnetotransport results of the single dot, we would like to point out that the MR of the bottom Au layer served as electrical contacts has a very rare effect on the top magnetic dots. The characteristics of the MR of the Au layer follow the B^2 law due to deflection of the moving carrier by Lorentz force. In our measuring field range, -50 kOe$\leq H \leq$50 kOe, the MR ratio of Au is about 0.002%/square and is relatively small compared with that of the magnetic dot.

We measured the MR of a series of different diameter Permalloy dots, from 0.3 to 5 μm, in different field orientations. The MRs of three dots with diameters of 0.6, 1, and 5 μm are plotted in Fig. 3. Here, ΔR is defined as $R(H)-R(H_{\text{saturation}})$ and MR is defined as $\Delta R/R(H_{\text{saturation}})$. Figures 3(a), 3(c), and 3(e) are $\Delta R_\perp$ curves with a magnetic field applied perpendicular to the dot plane. The signs of $MR_\perp$ of all samples are negative independent of the dot diameter. However, there are systematic changes in the $MR_\perp$ curves with the dot diameter. A clear hysteretic loop appears for the 5 μm dot while reversible loops for the two other samples. This is evidence that magnetotransport is sensitive to the domain structure. From MFM and magnetization measurements, a sample with a diameter of less than 2 μm has a vortex state at remanence. At saturation field all local moments are aligned with a field resulting in a 90° angle relative to measuring current and a lowest net resistance. Let α represent the angle between magnetization and measuring current. As the field is reduced, some moments start to lie in the dot plane resulting in different α values ($\alpha \neq 90°$). Based on the anisotropic magnetoresistive (AMR) effect, resistance change is proportional to $\cos^2 \alpha$ and, hence, resistance is a maximum at remanence where all moments lie in the dot plane forming a vortex state. The magnetization curve is reversible and so is the $MR_{\perp}$ curve. The scenario was still observed in a 0.3 μm Py dot. A sample with a diameter larger than 2 μm has a multidomain structure at remanence. The hysteretic MR curve corresponds to a hysteretic MH curve.

We also checked the evolution of $MR_{\parallel}$ where the magnetic field is applied along the measuring current in the dot plane. As shown in Figs. 3(b), 3(d), and 3(f), $\Delta R_{\parallel}$ is positive. At saturation field, all local moments are aligned with current resulting in $\alpha=0°$ and a maximum net resistance. The systematic correlation between magnetization moment and magnetotransport is similar to $MR_{\perp}$. There is slightly hysteresis in the $MR_{\parallel}$ loops in Figs. 3(b) and 3(d) due to the different entrances of the vortex core when H is parallel to the dot plane. Recent work on $MR_{\parallel}$ of a 1 μm Permalloy dot[12] is in consistence with our results. A slight difference in shape may be caused by the contact configuration.

The reversible MR behaviors observed in submicron dots with a vortex state can be qualitatively attributed to the ordinary AMR effect.[12] MR is reversible corresponding to the reversible change between two stable states, the single-domain state at saturation field and the vortex state at remanence. Quantitative analysis is still in process. When the dot size is increased and approaches to the critical length, where the magnetostatic energy overcomes the domain wall energy, the multidomain state becomes a preferably stable configuration at remanence and the clear hysteretic loops appear in the MR. This is a very clear evidence for the occurrence of transition from the vortex state to the multidomain state by the electrical transport investigation.

In summary, a special electrical contact configuration was designed for the MR study of any single submicron magnetic dot. The MFM images and magnetization measurements confirm that our 45 nm thick Permalloy dots can have the vortex state for a diameter of less than 2 μm and the multidomain state for larger dots. The behaviors of MR depend on the domain structures. The clear change in the MR shape occurs when the domain structure changes from vortex to multidomain states. Hence, our results imply that the magnetotransport can be a tool to detect the magnetic domain structure of a dot.

ACKNOWLEDGMENTS

MFM images were taken in the advance storage thin film laboratory of Dr. C. H. Lai. Magnetic moment measurements were made in the superconducting and magnetism laboratory of Dr. J. Y. Lin. This work was supported by the NSC of Taiwan grant under Project Nos. NSC94-2112-M-009-030 and NSC94-2120-M-009-002.

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[13] Details of the circuit analysis will be published somewhere else. Resistance across two voltage leads is equal to $(N+1)R_{Au}+N(1/R_{Au}+1/R_{dot})^{-1}$ where R_{Au} can be obtained by measuring a bare Au strip.