行政院國家科學委員會補助專題研究計畫期末報告

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介觀鐵磁環與點的電子傳輸與微磁態相關性探討

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□國際合作研究計畫國外研究報告書一份

執行單位：國立交通大學電子物理系

中　華　民　國　95　年　11　月　30　日

行政院國家科學委員會專題研究計畫成果報告

介觀鐵磁環與點的電子傳輸與微磁態相關性探討

The correlation between magneto-transport and micro-magnetic domain configuration in mesoscopic ferromagnetic dots

計畫編號：NSC 94-2112-M-009-030
執行期限：94 年 8 月 1 日至 94 年 9 月 30 日

主持人：許世英　　國立交通大學電子物理系

一、中文摘要

我們成功地利用特殊電極安排研究次微米大小的鐵磁點的磁電阻，一系列 45 奈米厚 Py 磁點顯現在直徑遞減至 1.1 微米時的磁區結構改變了，而對應的磁電阻有展現不同行為[1]；磁電阻與磁區結構有很強的相關性，當磁點直徑小於 1.1 微米殘磁區結構為漩渦狀，而磁電阻展現可逆行為，反之，大的磁點具有多磁區結構，而展現遲滯現象的磁電阻；在這些多磁區結構的磁點，藉由原子力顯微鏡觀察發現為顆粒結構，並從而知道其平均顆粒大小會隨磁點大小改變，從每個磁點展現的遲滯磁阻決定的矯頑場會隨磁點內磁顆粒平均直徑減小而遞減，之間展現 $\boldsymbol{H_c} \propto \boldsymbol{R_g}^2$ 關係式[2]，一般已知矯頑場會與異向性能和交換場強度比值有關，根據任意異向性理論(Random Anisotropy model)，奈米晶格的鐵磁性材料的矯頑場會隨磁點內磁顆粒平均直徑減小而遞減，之間展現 $\boldsymbol{H_c} \propto \boldsymbol{R_g}^6$ 關係式[3]，然而若考慮我們的磁點厚度相對其他散射長度，應將三維系統改正為二維系統，如此任意異向性理論就可以解釋我們的結果[4]。同時磁點隨大小減小而增加高電阻行為主要來自顆粒邊界的散射。

關鍵詞：數百奈米尺度鐵磁點，磁漩渦結構，磁電阻，異向磁阻。

Abstract

We have used successfully a special contact configuration to study magneto-transport of any single submicron permalloy disk. A change in magnetic domain structure coincident with magneto-transport occurs at disk diameter ~1.1μm for 45nm thick Py disk.[1] A disk with a diameter of less than 1.1μm has a domain of vortex state at remanence and demonstrates similar reversible magnetoresistance behaviors. Meanwhile, larger disks have multi-domain structures and demonstrate the hysteretic behaviors in magnetoresistance. In this multi-domain regime, each single disk is composed of many grains and average grain size detected by atomic force microscope was found to decrease with decreasing disk diameter. Moreover, coercive field determined from hysteretic magnetoresistance also decreases with decreasing grain size in a relation that $\boldsymbol{H_c} \propto \boldsymbol{R_g}^2$. It has been known that coercive field depends on the relative ratio between anisotropy strength and exchange field strength.[2] According to the random-anisotropy model (RAM), H_c is expected to decrease with a decrease in grain size by R_g^6 for nanocrystalline ferromagnets.[3] Nevertheless, our results can be obtained using RAM taken account of the dimensionality change from three to two.[4] We also show that grain-boundary scattering

is the dominant source of resistance for these dots with multi-domain.

Keywords: submicron magnetic dots, vortex domain, magneto-transport, AMR.

二、緣由與目的

Recent advances in the nanofabrication methods have made the possibility of studying the magnetism at small length scale, in which can be potential applications in high density recording and modern magneto-electronic devices. The magnetic reversal process in circular[5], square[6] or other shape dots[7] has been studied for a while by μ-MOKE[5-8], MFM[8-10], STM[11], Lorentz-Microscopy[12], and Electron Holography[13]. 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 multi-domain and single domain states the flux closure state is generated during reversal process and is called the vortex state. From the practical viewpoint, the studies of magnetoresistance (MR) are very important. New transport phenomena may occur for structures in sufficiently reduced dimensions. Up to now, almost all MR studies in nanostructures are focused on nanowires[14] and rings[15]. The MR study of a single dot is very rare due to the probing difficulty. Recently, Vavassori ***et al***.[16] reported the first MR measurement in a circular permalloy dot with diameter 1 μm and thickness 25nm. In their device, four 10nm Au leads were arranged underneath the dot at four corners for electrical contacts resulting in a non-uniform current distribution and uncertain dot domain reversal processes. Here we used a simple design of electric contact configuration to obtain MR of a single sub-μm magnetic dot. In this work, the magnetoresistance(MR) of a series of different size permalloy dots was measured to investigate the correlation between domain-structure and magneto-transport properties.

三、實驗方法

Our samples were prepared by standard e-beam lithography, thermal evaporation, and lift-off techniques. The circular permalloy dots have thickness of 45nm 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 electrical measurement, several identical dots were distributed evenly atop a 30nm thick Au strip with a width same as the diameter of the dots. Contact configuration was arranged for 4-terminal electrical measurement. Fig.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 completely disk-like shape and the separation between neighboring dots in each area is about the same as dot diameter.

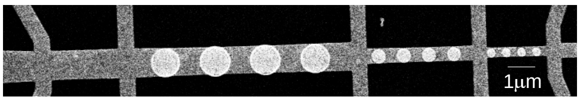

Fig.1. SEM image of one sample. Measuring current is applied along the long Au strip and resistance is measured between two neighboring vertical Au contacts. In this device, four sections are arranged for studies of bare Au and permalloy dots with 1, 0.6, and 0.3 μm in diameter (from left to right).

Magnetic structure and magneto-transport measurements were performed. The former was obtained using magnetic force microscope (Nanoscope Dimension 3100) in the tapping/lift mode. The magnetic configurations were imaged at a lift height of 100nm 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 single dot. Single dot behavior can be extracted simply 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 dot and Au sheet in parallel. Independent experiment of a sequence of N confirmed such circuit analysis[17]. Hence, electrical transport of a single dot is easily obtained using such contact configuration.

四、實驗結果

(A) Magneto-transport of a series of magnetic dots from multi-domain to vortex domain

It has been known that magnetic structure of a magnetic dot depends on its geometrical factors such as thickness and dot size. To check the magnetization state of our 45nm thick permalloy dots we investigated the domain structure using MFM at room temperature. Fig.2(a) shows MFM images of two samples with 5 and 0.8 μm in diameter, respectively, at remanence. Prior to image scanning, dots were magnetized in 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 0.8μm dot corresponding to the turned-down vortex core, while a complicated combination of dark and bright areas is present for 5μm dot. In Fig.2(b) 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 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 vortex state. MFM and magnetization moment investigations show that dots with diameter less than 2μm are in vortex states and dot with diameter of 5μm is in multi-domain state, at remanence.

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

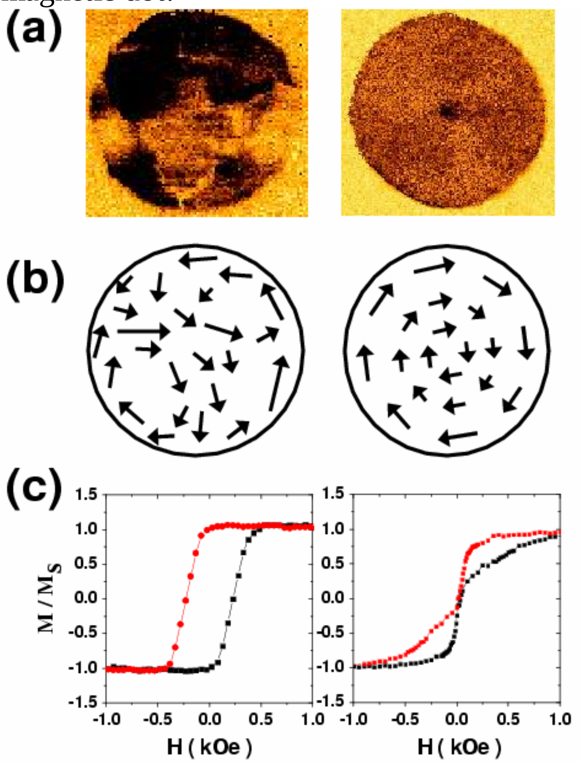

Fig. 2(a) MFM images of two dots with 5 (left) and 0.8 μm (right) in diameter, respectively. (b) The arrow line sketches to show two domain structures in (a). (c) Normalized magnetization moments as a function of applied field H of two dot arrays with 5 (left) and 0.8 (right) μm in diameter.

We measured MR of a series of different diameter permalloy dots, from 0.3 to 5 μm, in different field orientations. MRs of three dots with diameters, 0.6, 1, and 5μm are plotted in Fig.3. Here, ΔR is defined as $R(H)-R(H_{saturation})$ and MR is defined as $\Delta R/R(H_{saturation})$. Fig.3(a),(c), and (e) are $\Delta R_{\perp}$ curves with magnetic field applied perpendicular to dot plane. The signs of $MR_{\perp}$ of all samples are negative independent of dot diameter. However, there are systematic changes in $MR_{\perp}$ curves with dot diameter. A clear hysteretic loop appears for the 5μm dot while reversible loops for two other samples.

This is evidence that magneto-transport is sensitive to domain structure. From MFM and magnetization measurements, sample with diameter less than 2μm has a vortex state at remanence. At saturation field all local moments are aligned with field resulting in a 90^{o} angle relative to measuring current and a lowest net resistance. Let α represents the angle between magnetization and measuring current. As the field is reduced, some moments start to lie in dot plane resulting in different α values ($\alpha \neq 90^{o}$). Based on the AMR effect, resistance change is proportional to $\cos^2\alpha$ and hence, resistance is a maximum at remanence where all moments lie in dot pane forming a vortex state. The magnetization curve is reversible and so is the $MR_{\perp}$ curve. The scenario was still observed in 0.3μm Py dot. Sample with diameter larger than 2μm has multi-domain structure at remanence. The hysteretic MR curve corresponds to a hysteretic MH curve.

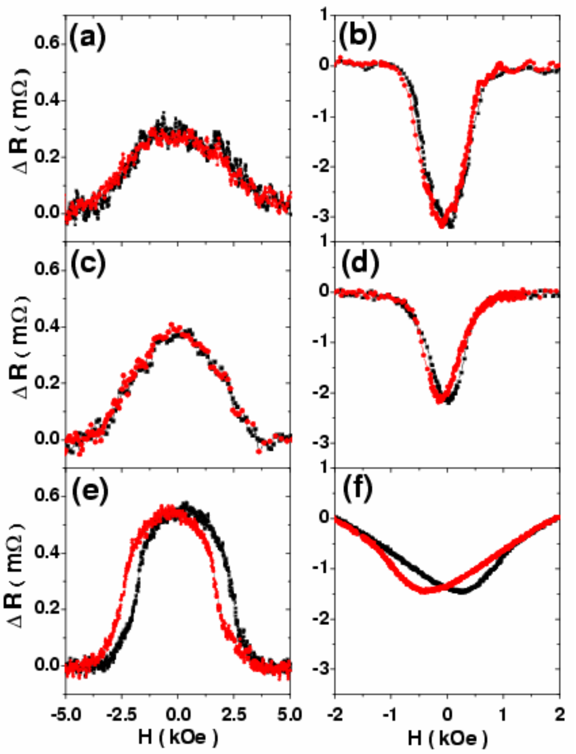

Fig. 3 The MR behaviors of three different diameter permalloy dots, 0.6μm (a,b), 1μm (c,d), and 5μm (e,f), respectively, at T=5K. Left figures (a)(c)(e) are $\Delta R_{\perp}$ where field is perpendicular to film plane and right figures (b)(d)(f) are $\Delta R_{//}$ where the field is parallel to both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

We also checked evolution of $MR_{//}$ where the magnetic field is applied along measuring current in dot plane. As shown in Fig.3(b), (d), and (f), $\Delta R_{//}$ is positive. At saturation field, all local moments are aligned with current resulting in $\alpha=0^{o}$ and a maximum net resistance. The systematic correlation between magnetization moment and magneto-transport is similar to $MR_{\perp}$. There are slightly hysteresis in $MR_{//}$ loops in Fig.3 (b) and (d) due to different entrances of vortex core when H is parallel to dot plane. Recent work on $MR_{//}$ of 1μm Permalloy dot[16] is in consistence with our results. A slight difference in shape may be caused by the contact configuration.

The reversible MR behaviors observed in sub-micron dots with vortex state can be qualitatively attributed to the ordinary AMR effect[16]. 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 multi-domain becomes a preferably stable configuration at remanence and the clear hysteretic loops appear in MR. This is a very clear evidence for the occurrence of transition from the vortex state to the multi-domain state by the electrical transport investigation.

(B) Grain-boundary scattering in sub-micron Py disks

In the bulk materials, the resistivity comes from the electron scattering with phonons and point defects. It has been known that the electrical resistivity of thin metallic films increase once the film thickness is less than the bulk electronic mean free path. Grain boundary and surface scatterings will increase the resistivity of thin films and confined structures. Initial work by Fuchs and Sondheimer[18] (FS theory) attributed this effect to diffuse scattering at the film boundaries, which essentially imposes a restriction on the mean free path. After that, some work showed that a reduction of the grain size in thin films can result in a significant resistivity increase due to scattering with the grain boundaries, as described by Mayadas and Shatzks (MS theory)[19]. In the MS theory, three types of electron scattering mechanisms are simultaneous consideration: an isotropic background scattering(due to phonons and point defects),scattering due to a distribution of planar potentials(grain boundary),and scattering due to the external surfaces. The grain-boundary component of resistivity is given by

$$\frac{\rho_0}{\rho}=3\left[\frac{1}{3}-\frac{\alpha}{2}+\alpha^2-\alpha^3\ln\left(1+\frac{1}{\alpha}\right)\right] \qquad (1)$$
$$\alpha=\frac{\lambda}{\boldsymbol{R_g}}\frac{\boldsymbol{R}}{1-\boldsymbol{R}}$$

where λ is the mean free path, $\boldsymbol{R_g}$ is the mean grain size, and R is the grain-boundary reflection coefficient。 Besides modulating the conditions of fabrication, the confinement in dimension also can vary the grain size systematically[20].

In the permalloy dots system, the single dot resistance increases with decreasing the dot size. This behavior may be caused by the increases of surface scattering and the number of grain boundaries for smaller dots. As shown in Fig.4, the AFM images of the dots, the mean grain size indeed decreases with decreasing dot size. We can analytically estimate the effective grain size distribution as a function of the dot diameter. For the grain-structured samples, coercive field depends on grain size following that $H_c \propto \boldsymbol{R_g}^2$. The estimated values of $\boldsymbol{R_g}$ from AFM images and coercive fields determined from longitudinal and transverse magnetoresistances demonstrate such a relation shown as a log-log plot in Fig.5.

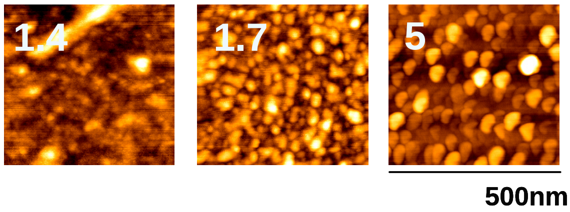

Fig. 4 AFM images of three Py disk with diameters , 1.4, 1.7 and 5μm (from left to right).

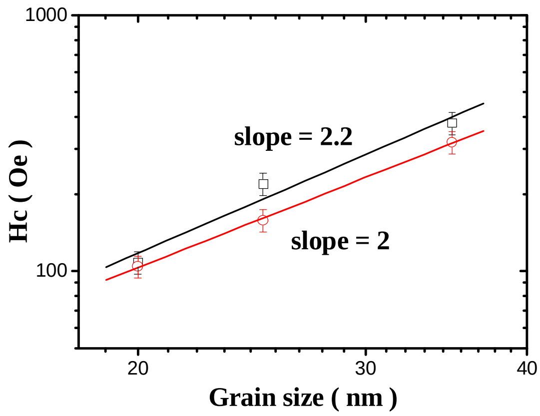

Fig..5 Logarithmic plot of coercive field obtain from LMR (black) and TMR (red) and grain size. Lines are least square root fits.

We attempt to fit the MS theory to data using the intrinsic film resistivity $\rho_0=16\mu\Omega \boldsymbol{cm}$ for bulk Permalloy and the low temperature mean free path $\lambda=5.5\boldsymbol{nm}$. Fig.6 show the experimental data and the least-sqrt fit using the eq.(1) with the fitting parameter $\boldsymbol{R}=0.3$. This value of R is close to the previous report[19]. The fitting curve describes very well our data for the dot with d≥1.1μm. When the dot diameter is less than 1μm, the resistance increases rapidly with decreasing dot diameter and can not be described by Eq.(1) any more. Therefore, when the dot diameter above 1.1μm(in multi-domain), grain-boundary scattering is the dominant source of resistance. Once dot diameter is less than 1μm (vortex state), there is additional surface scattering must be taken into account.

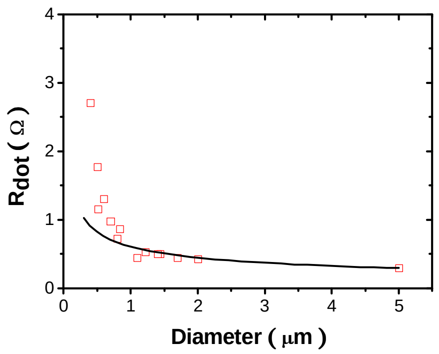

Fig. 6 Logarithmic plot of single dot resistance versus dot diameter. The open boxes are the experimental data Line is the least square root fit to Eq.(1).

四、結論

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

For the multi-domain disks, our results can be described by random anisotropy model in two dimensions. The increase of resistivity with decreasing dot diameter can be attributed to the grain boundary scattering due to the reduction of average grain size.

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