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2010 J. Phys.: Conf. Ser. 200 032037

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Magnetic vortex structures probed by magnetotransport in sub-micron permalloy disks

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Abstract. We have successfully used magneto-transport measurement to study magnetization reversal of domain structure in single sub-micron magnetic disks of various sizes, $300\text{nm} \leq \text{diameter} \leq 5\mu\text{m}$ and $36\text{nm} \leq \text{thickness} \leq 48\text{nm}$. The magnetoresistance (MR) resulted from the anisotropic magnetoresistance effect can reveal the magnetization reversal of a single disk as confirmed by the magnetic force microscopic results. For a fixed thickness, the remanent domain state can transit from the multi-domain to vortex states by decreasing the disk diameter. Here, the nucleation and annihilation fields of vortex core are determined from disk's hysteretic MR and analytically described by the micromagnetic LLG calculation incorporated with the "rigid" vortex model developed by Guslienko *et al.* under the consideration of magnetostatic, exchange, and Zeeman energies.

1. Introduction

The investigation of the magnetic reversal processes in micro- and nano- patterned ferromagnetic systems is currently stimulating intense theoretical and practical attentions because of their importance in fundamental physics and valuable applications in data storage and magnetic logic.[1, 2, 3, 4] For circular disks of soft magnet, the short range exchange energy becomes very important as the dimension is decreased. Between the multi-domain and single-domain states, the flux-closure configuration appears during the reversal process and is so called vortex state.[5, 6, 7] Due to the difficulty in measuring an individual small disk, there is rare experimental data in exploring the magnetization reversal under the magnetic fields through the nucleation, displacement, and annihilation of magnetic vortex.[8, 9, 10] Previous study using Lorentz transmission electron microscopy (LTEM) found that the reversal process depends on the disk geometry in qualitative agreement with micromagnetic simulation for thinner disks.[10, 11] Here, we make a systematic investigation in thicker permalloy disks using magneto-transport and make comparisons with other data and theoretical calculation.

2. Experimental details

Our permalloy (Py, $\text{Ni}_{80}\text{Fe}_{20}$) disks are prepared by standard e-beam lithography, thermal evaporation, and lift-off techniques. Two series of disks have 36 and 48nm in thickness (t), respectively. The diameters (D) span from 0.3 to $5\mu\text{m}$. In order to investigate the magneto-transport of Py disks, several identical disks are distributed evenly atop a 30nm thick Au strip of a width same as the diameter of the disks. Single disk behavior can be extracted simply by using Kirchhoff's circuit theorem.[9] One thing need to be pointed out is that the magnetoresistance of

Au strip is less than 0.001%, relatively small compared with that of Py disk in our magnetic fields ($\leq 2.3\text{kOe}$). Moreover, the interdisk spacing is the same as D and the interactions between disks can be neglected. The electrical measurements are performed using a standard four terminal ac lock-in technique in a pumped ^4He cryostat and at the center of an electromagnet. The magnetoresistance measurements are made in two configurations. The magnetic field always lies in the sample plane. In the longitudinal geometry, magnetic field is applied along the current direction, while in the transverse geometry, magnetic field is perpendicular to the current.

3. Results and Discussion

It has been well known that a circularly magnetic disk may have the vortex structure in remanence depending on its geometry. There are the nucleation (H_n) and annihilation (H_a) fields characterizing the formation of the magnetic vortex. When magnetic field is decreased from the saturation field (H_s), the vortex nucleates in H_n with an abrupt reduction in magnetic moment. With continuously decreasing magnetic field, the vortex core is moving toward the disk center. In remanence ($H=0$), the core resides at the center. When H is applied to the opposite direction, the core keeps moving until H_a where the vortex vanishes completely. According to the micromagnetic calculation using LGG model, the moment distribution of the disk in magnetic fields can be obtained.

Figure 1(a) shows the longitudinal and transverse magnetoresistances of a disk of $D=0.9\ \mu\text{m}$ and $t=48\text{nm}$. Accompanied with anisotropic magnetoresistance effect, the hysteretic behavior is in consistency with the magnetization reversal of the formation of magnetic vortex. At saturation, all moments align with the magnetic field leading to that resistance is the maximum for LMR ($I\parallel H$) and the minimum for TMR ($I\perp H$), respectively. As being close to H_n , resistance starts to decrease for LMR while increase for TMR due to the sudden loss of moment along the field direction. With further decreasing H , LMR (TMR) decreases (increases) continuously until $H=0$ where resistance is the minimum (maximum). Moreover, as seen in Fig.1(a), both resistances in remanence are exactly the same independent of the current direction since the vortex core is at the disk center. Evident by the remanent magnetic force microscopic (MFM) image of the disk in the inset of Fig.1(a), the only contrast spot at the disk center corresponds to the turned-down vortex core. When the magnetic field is switched to the opposite direction, LMR (TMR) increases (decreases) continuously with increasing magnetic field until H_a . Beyond H_a , the disk is back to the saturation status. For both LMR and TMR in Fig.1(a), there is a reversible part of the loop corresponding to the linear movement of the vortex core with the direction normal to the magnetic field. The hysteretic part lobes correspond to vortex creation and annihilation at the edge of the disk. Our observed magnetotransport behavior indeed agrees with the expected magnetization loop and moment configuration simulation for a magnetic disk of vortex domain.

With increasing the disk diameter, the remanent state may transit to the multi-domain. As shown in the inset of Fig.1(b) for a big disk of $D=3\ \mu\text{m}$, a complicated combination of dark and bright area is present in its remanent MFM image. Corresponding LMR and TMR are plotted in Fig.1(b) demonstrating the typical hysteretic MR curves for a magnet of multi-domain state. The critical diameter for the transition from vortex to multi-domain states is around $1.9\ \mu\text{m}$ for the 48nm thick Py disks. It decreases slightly with decreasing the disk thickness.

From LMR and TMR curves, both H_n and H_a can be easily determined. We have made a systematic study in two series of Py disks. Data is shown in Fig.2, (a) $t=48\text{nm}$ and (b) $t=36\text{nm}$, respectively. As seen, both H_n and H_a increase as the disk diameter decreases. A geometry dependence of the annihilation field was reported by Schneider *et al.* by LTEM in thinner disks ($t\leq 20\text{nm}$). [10] Our results coincide with their data. Since our disks are thicker, the annihilation fields may be larger when D is the same. Furthermore, it increases rapidly for smaller disks upon the ratio of D/t . [10] Comparison between our two series of different thicknesses exhibits that the

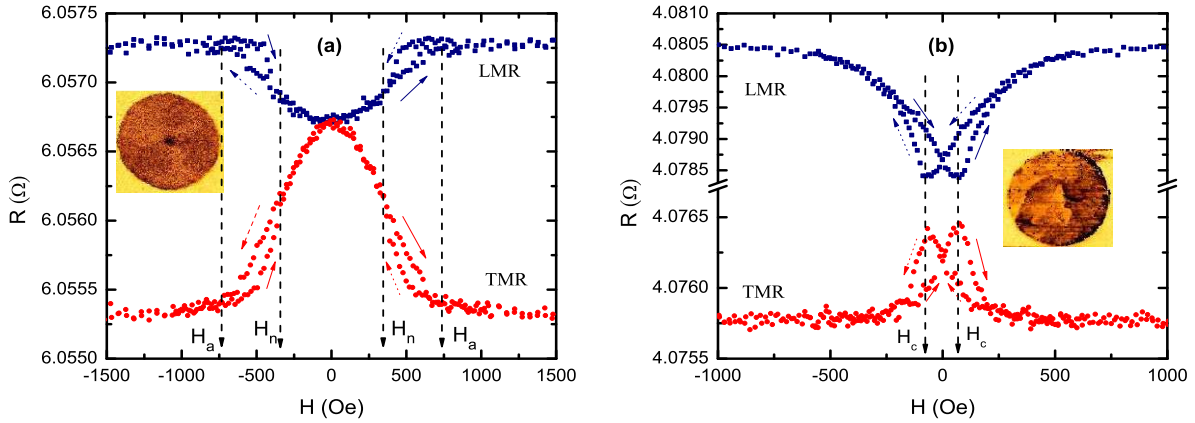


Figure 1. Longitudinal (blue squares) and transverse (red circles) magnetoresistances of two permalloy disks, (a) $D=0.9\mu\text{m}$ and (b) $D=3\mu\text{m}$, at $T=10\text{K}$. Insets: MFM images of each disk of the same geometry in remanence at room temperature.

the difference of annihilation fields is small for large disks, within 50Oe, and becomes pronounced for small disks. The LTEM study did not report the nucleation field while suggesting a S-shaped nucleation mode for disks of $D \geq 350\text{nm}$. [10] The large deviation in resistance from the saturation value before reaching H_n observed in our data may support their finding.

Gusliencko *et al.* have developed an analytical model using the one-vortex approximation (“rigid” vortex model) to describe both characteristic fields, H_n and H_a . [11] In remanence, the vortex core stays at the disk center. When H is applied, the core is pushed toward the disk perimeter to increase the net moment along H . However the vortex keeps its spin distribution while being displaced and the state is treated as an off-center rigid vortex structure. By minimize the total energy which consists of the exchange, magnetostatic, and Zeeman energies, the equilibrium displacement of the core can be obtained in terms of the disk geometry (D , t) and magnetic field H . The annihilation field is determined when the core reaches the disk perimeter. [11] The analytical expression for the annihilation field is given by

$$H_a = M_s \left(4\pi F_1(\beta) - \left(\frac{2\ell_{ex}}{D} \right)^2 \right) \quad (1)$$

M_s is the saturation magnetization. ℓ_{ex} is the exchange length. Function F_1 depends on the aspect ratio β , $2t/D$, in proportion to the in-plane demagnetizing factor. Black lines in Fig.2 are obtained using Eq.(1) and fall well on top of data. The annihilation field is primarily dominated by the magnetostatic energy through F_1 . It is produced by the surface charges along the disk perimeter when the vortex core leaves the disk center. With decreasing D , the distance between the positive and negative magnetic charges is reduced leading to a significant increase in the magnetostatic energy (F_1). Therefore, H_a increases with decreasing the disk diameter.

As to the nucleation field, it is the maximum field in which the uniformly magnetic state at saturation becomes unstable. At saturation, the vortex center is outside the disk and at an infinite distance from the disk center. The total energy is calculated in terms of the vortex center displacement relative to the disk center. The stable spin distribution of vortex structure with a finite vortex center displacement is resolved at H_n . [11] The analytical expression for the nucleation field is given by

$$H_n = M_s \left(4\pi F(\beta) - 4 \left(\frac{2\ell_{ex}}{D} \right)^2 \right) \quad (2)$$

The analytical calculation using Eq.(2) gives a qualitative agreement with our data on the disk geometry dependent H_n . However the calculated value is rather smaller. The red lines in Fig.2

are the triple of the calculated values. Surprisingly, experimental data follow very well with the red lines. The underestimate of H_n may be attributed to the initial assumption of C-shaped nucleation mode in the rigid vortex model. From our MR and other LTEM results, the S-shaped nucleation mode before reaching H_n is evident for the large disks and need to be taken into account in the theoretical analysis.[10, 11]

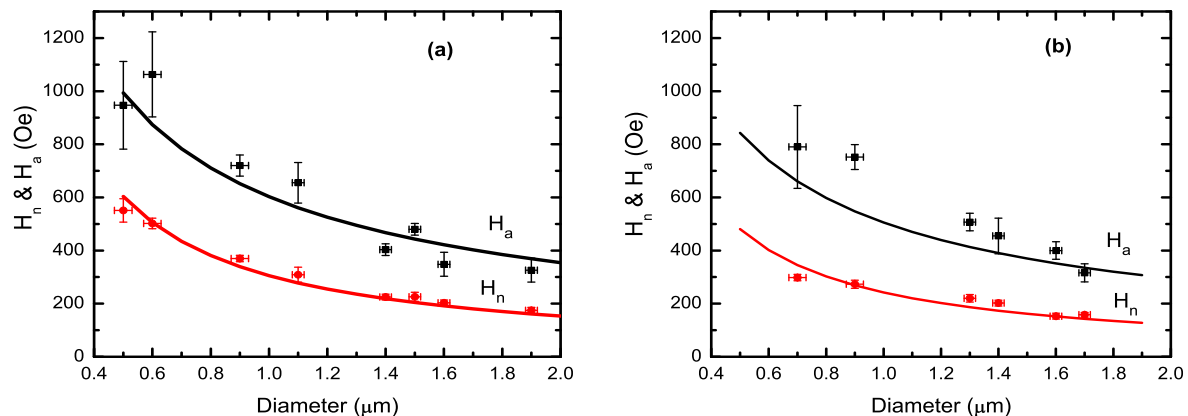


Figure 2. H_a (black squares) and H_n (red circles) obtained from magnetoresistances versus the disk diameter for two series of permalloy disks with (a) $t=48\text{nm}$ and (b) $t=36\text{nm}$, respectively. Black lines are the analytical results using Eq.(1) for H_a . Red lines are the triple of the analytical results using Eq.(2) for H_n .

4. Conclusions

A special electrical contact configuration is designed successfully to investigate the magnetization reversal of the individual submicron magnetic disk. The nucleation and annihilation fields are obtained from the magnetoresistances for disks of magnetic vortex structure. The analytical calculation based on the rigid vortex model gives a quantitative agreement with our measured annihilation field, while giving about one third of our measured nucleation field. The deviation may be due to the imperfect round and edge roughness induced vortex deformation that is neglected in the model. However, data show a qualitative dependence on the disk geometry as the theoretical expectation. Both characteristic fields increase with decreasing the disk diameter.

Acknowledgments

The remanent MFM images are taken by a magnetic force microscope in the advance storage thin film laboratory of Dr.CH Lai. This work was supported by NSC grant in Taiwan under project No NSC96-2112-M009-030-MY3 and MOE ATU program.

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