Determination of the magnetic anisotropy constant of Cu/Fe/SiO_2/Si by a magneto-optical Kerr effect susceptometer*

Jia Yi-Jiao(贾义娇)[a)b)], He Wei(何 为)[a)], Ye Jun(叶 军)[a)c)], Hu Bo(胡 泊)[a)],
Chen Zi-Yu(陈子瑜)[c)], Gao You-Hui(高有辉)[b)], Zhang Xiang-Qun(张向群)[a)],
Yang Hai-Tao(杨海涛)[a)], and Cheng Zhao-Hua(成昭华)[a)†]

[a)] *State Key Laboratory of Magnetism and Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing* 100190, *China*
[b)] *Department of Physics, Beijing Normal University, Beijing* 100875, *China*
[c)] *Department of Physics, Beihang University, Beijing* 100191, *China*

(Received 25 June 2013; revised manuscript received 29 August 2013; published 3 December 2013)

The magneto-optical Kerr effect susceptometry technique is proposed to determine the uniaxial magnetic anisotropy (UMA) constant K_u. The magnetic properties of Cu/Fe/SiO_2/Si grown by dc magnetron sputtering were investigated. The in-plane uniaxial magnetic anisotropy was probed by the magneto-optical Kerr effect (MOKE). The value of UMA, $K_u = 2.5\times10^3$ J/m^3, was simulated from the field dependence of ac susceptibility along the hard axis according to the Stoner–Wohlfarth (S–W) model, which is consistent with $K_u = 2.7\times10^3$ J/m^3 calculated from the magnetic hysteresis loops. Our results show that the magneto-optical Kerr effect susceptometry can be employed to determine the magnetic anisotropy constant owing to its high sensitivity.

Keywords: ac susceptibility, magnetic anisotropy, magneto-optical Kerr effect susceptometry

PACS: 75.30.Gw, 75.50.Bb, 75.30.Cr, 75.60.Jk **DOI:** 10.1088/1674-1056/23/1/017502

1. Introduction

Low-dimensional magnetic nanostructures have attracted great attention due to their potential applications in information storage and magnetic sensors, as well as their wealth of distinctive physical properties for fundamental research.[1,2] The magnetic anisotropy is not only the origin of long-range-magnetic-order in low dimensional system,[3,4] but also plays a vital role in determining the magnetic properties of magnetically hard materials, magnetically soft materials,[5] high-frequency magnetic materials,[6] ultrahigh density magnetic recording media and spintronic materials.[7] The magnetic anisotropy constant can be determined by various methods, such as magnetic hysteresis loop measurement, torque measurement,[8] ferromagnetic resonance (FMR),[9] rotational magneto-optic Kerr effect (ROTMOKE),[10] magnetic transverse biased initial inverse susceptibility and torque (TBIIST)[11] and anisotropic magnetoresistance (AMR).[12–18] Since the coherent domain rotation magnetization reversal for ultrathin film does not always occur in the easy magnetization direction, it is difficult to determine the magnetic anisotropy constant precisely from the magnetization hysteresis loops.

A versatile tool in modern magnetic material research, the ac-mode magneto-optical Kerr effect technique,[19] has been utilized in the studies of magnetic phase transitions,[20,21] magnetic domain responses[22,23] and exchange biases in magnetic thin films[24] owing to its high sensitivity. The magnetization is forced to move back and forth reversibly around the equilibrium position when a very small ac field is applied either parallel or perpendicular to the dc field. The magnetic anisotropy constant can be obtained by fitting the reversible magnetization process in terms of the Stoner–Wohlfarth (S–W) model. Here, we report our development of an ac-mode magneto-optical Kerr effect technique to determine the uniaxial magnetic anisotropy constant K_u of a ferromagnetic thin film. To test the magneto-optical Kerr effect susceptometry method, we use a sample of Cu/Fe/SiO_2/Si grown by dc magnetron sputtering. The sample is checked by magneto-optical Kerr effect magnetometry. The magnetic hysteresis loops for the easy and hard magnetization directions can be fitted well on the basis of the S–W model, suggesting a coherent magnetization reversal. On the basis of the field dependence of the ac susceptibility, the uniaxial magnetic anisotropy constant can be obtained. The consistent values of uniaxial magnetic anisotropy constant obtained from the field dependence of ac susceptibility and the Kerr hysteresis loops prove that the magneto-optical Kerr effect susceptometry can be used as a powerful tool to determine the magnetic anisotropy constant.

*Project supported by the National Basic Research Program of China (Grant Nos. 2009CB929201, 2011CB921801, and 2012CB933102) and the National Natural Science Foundation of China (Grant Nos. 50931006, 11034004, 51021061, and 11274033).

†Corresponding author. E-mail: zhcheng@iphy.ac.cn

© 2014 Chinese Physical Society and IOP Publishing Ltd

2. Experiment

The sample was grown by dc magnetron sputtering in 0.5 Pa of Ar. The base pressure before deposition was 7.4×10^{-4} Pa and the substrate was a commercial Si wafer with a surface of naturally formed silica. An Fe film was deposited directly on the top of the Si substrate by reactive sputtering[25] of Fe in an argon atmosphere at room temperature. The plasma current was 0.15 A and the distance between the target and the substrate was set at 14 cm. Copper was deposited on the top of the Fe/SiO_2/Si to prevent oxidation. The film thickness was measured by a stylus profiler (Dektak 6 mol/L) and the thickness was 40 nm with Cu capping layers.

Magnetic properties were probed by *ex situ* longitudinal MOKE at room temperature. The dc MOKE apparatus,[24] which was modified for measurements of ac susceptibility, is schematically shown in Fig. 1. We applied an ac field $h(t)$ either parallel or perpendicular to the dc field H in the film plane. The dc field was supplied by an electromagnet whose power supply was computer controlled. A Helmholtz pair of coils that was placed either parallel or perpendicular to the dc component provided a very small oscillating field. As a result, the ac field, in the same frequency as $h(t)$, was sent out to the photodiode, resulting in an ac current which was then phase detected by a lock-in amplifier. The parallel ac susceptibility ($\chi_{\parallel}$) and perpendicular ac susceptibility ($\chi_{\perp}$) could be measured as a function of the dc field. The magnetization curves M versus H were obtained by MOKE using the same experimental apparatus described above.

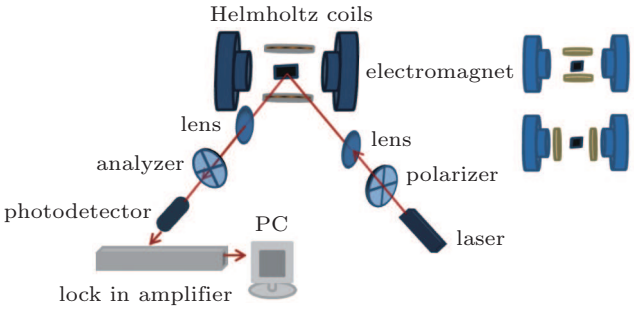


Fig. 1. (color online) Block diagram of the experimental apparatus used to measure the ac susceptibility. The Helmholtz pair of coils in the diagram is placed either parallel or perpendicular to the dc component.

3. Results and discussion

The magnetic properties of Cu/Fe/SiO_2/Si films were probed by *ex situ* longitudinal MOKE at room temperature. An in-plane uniaxial magnetic anisotropy was observed from the MOKE hysteresis loops at various magnetic field orientations as defined in the inset of Fig. 2. The typical hysteresis loops show a square shape along the easy axis ($\phi = 0°$) and a sheared one with no remanence along the hard axis ($\phi = 90°$) (Fig. 2). Owing to the polycrystalline Si substrate, the magnetocrystalline anisotropy can be neglected. The in-plane uniaxial magnetic anisotropy originates not only from the strain-induced magnetic anisotropy between Fe and Cu but also from the polycrystalline Si substrate.[26,27] In addition, the sample was obtained by dc magnetron sputtering. The uniaxial anisotropy can be attributed to a stray magnetic field caused by the cathode target.[28]

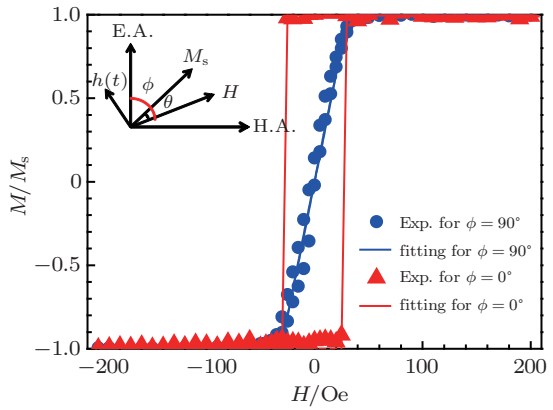


Fig. 2. (color online) Experimental and simulated magnetic hysteresis loops of Cu/Fe/SiO_2/Si measured by MOKE. Typical in-plane magnetic hysteresis loops in the directions of the hard axis ($\phi = 90°$) and the easy axis ($\phi = 0°$). The solid symbols and lines are the experimental data and the fitting curves simulated by the S–W model, respectively. Inset: the coordinate system for measurements.

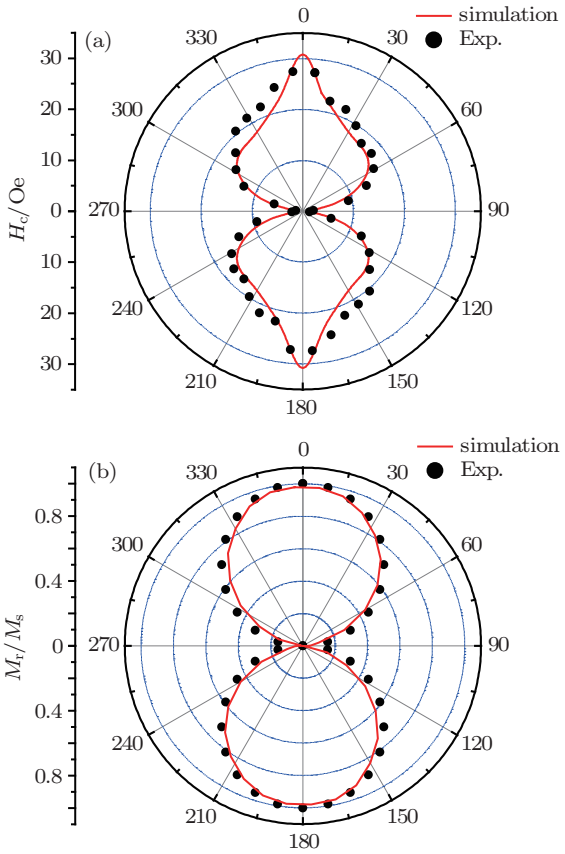


Fig. 3. (color online) Angular dependences of (a) the coercive field H_c and (b) normalized remanence M_r/M_s obtained from the experimental hysteresis loops and the simulation lines.

In order to determine the in-plane uniaxial magnetic anisotropy constant, the hysteresis loops for the easy magnetization direction and hard magnetic anisotropy were simulated on the basis of the S–W model. The simulated curves are in good agreement with the experimental data. Furthermore, we can also observe that the uniaxial magnetic anisotropy constants of the easy and hard axes are approximately the same, $K_u = 2.7\times10^3$ J/m^3, implying that the coherent domain rotation magnetization reversal takes place in both the easy and the hard magnetization directions.

Figures 3(a) and 3(b) present the measured and the simulated angular dependences of coercivity H_c and remanence ratio M_r/M_s, respectively. The shapes of the curves exhibit a typical symmetry of a magnetic film with uniaxial magnetic anisotropy.[26] The consistence between the simulated curves and the experimental data further confirms the coherent domain rotation magnetization reversal. The sample with coherent rotation magnetization reversal provides us with a good opportunity to verify the capability of the magneto-optical Kerr effect susceptometer for determining the magnetic anisotropy constant.

As illustrated in Fig. 4(a), there is no evident difference in the hysteresis loops of Fe/SiO_2/Si around the hard magnetization, i.e., $\phi = 90\pm9°$, which suggests that it is difficult to determine accurately the hard magnetization direction from the hysteresis loop measurements. In order to distinguish accurately the hard axis, the ac susceptibility around the hard axis was measured. It can be found that the field dependence of parallel ac susceptibility $\chi_\parallel$ in various directions is in accordance with (Fig. 4(b)) that of the first-order differential of the hysteresis loops dM/dH (Fig. 4(c)). Therefore, the ac field is just a perturbation to the dc magnetic field.

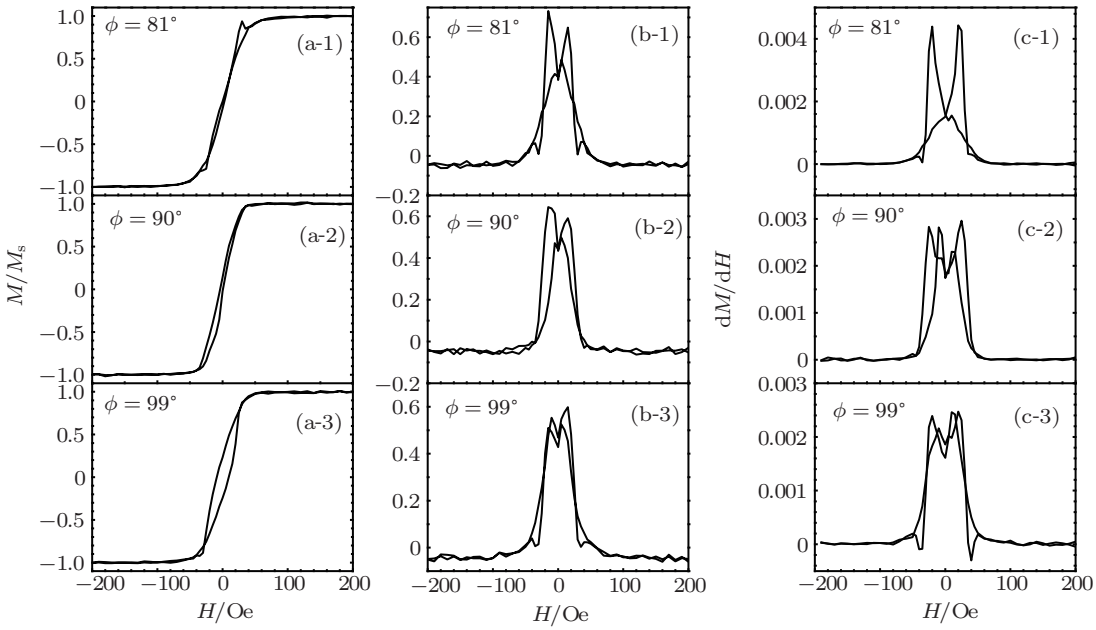


Fig. 4. (a) MOKE hysteresis loops and (b) parallel ac susceptibility ($\chi_\parallel$) as a function of the dc field obtained from the magneto-optical Kerr effect susceptometer and (c) the differential of the hysteresis loops for various directions around the hard axis ($\phi = 90\pm9°$).

On the other hand, the field dependence of perpendicular ac susceptibility $\chi_\perp$ for various directions around the hard axis is quite different (Fig. 5(a)). A tiny deviation from the hard magnetization direction results in a significant change in the $\chi_\perp \sim H$ curves. Therefore, the field dependence of $\chi_\perp$ can be employed to probe the hard magnetization axis exactly. The hard axis can also be determined exactly by ROT-MOKE.[10]

The perpendicular ac susceptibility can be defined as $\chi_\perp = \lim \Delta m/\Delta h$. First, we adopt the numerical simulation method and select the hard magnetization axis curve as a reference. Based on the S–W model, we assume that two mutually perpendicular magnetic fields, H and $h(t)$, are applied simultaneously in the sample plane. By taking the perpendicular ac field $h(t)$ into account, the total magnetic free energy per unit area of the ferromagnetic layer can be written as follows:

$$E = -\mu_0 MH\cos\theta - \mu_0 Mh(t)\sin\theta - K_u\cos^2(\phi-\theta), \quad (1)$$

where ϕ is the angle between the direction of the easy magnetization axis (E.A.) and the direction of the magnetic field H and θ is the angle between the magnetization M and the dc field H. The first two terms represent the interaction of the magnetization of the ferromagnetic layer with the applied fields H and $h(t)$. The third term represents the ferromagnetic uniaxial magnetic anisotropy energy and K_u is the uniaxial magnetic anisotropy constant of the ferromagnetic layer.

During the simulation, we use $M_s = 1.74\times10^6$ A/m for

Fe, $h = 7$ Oe and vary H from -200 Oe to 200 Oe. The value of $K_u = 2.5 \times 10^3$ J/m^3 can be obtained from the simulated curves of $\chi_\perp$ as a function of magnetic field H for various directions (Fig. 5(b)). By comparing the two simulated results, it can be proved that the magnetic anisotropy constant K_u from the perpendicular ac susceptibility curves in the direction of the hard axis is reasonable.

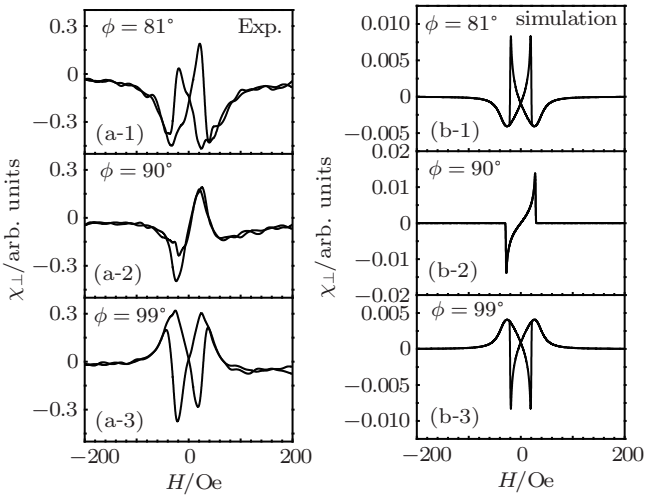


Fig. 5. Perpendicular ac susceptibility $\chi_\perp$ as a function of the dc field, obtained from (a) the magneto-optical Kerr effect susceptometer and (b) the simulations for various directions around the hard axis ($\phi = 90 \pm 9°$).

4. Conclusion

We put forward a new method to determine the magnetic anisotropy constant. The magnetic properties of the Cu/Fe/SiO_2/Si grown by dc magnetron sputtering were probed by MOKE and an ac-mode magneto-optical Kerr effect technique. Taking advantage of the high sensitivity of ac susceptibility, we can directly distinguish the directions of the hard and easy axes. The magnetic anisotropy constant K_u can be best fitted from the ac susceptibility curve, which is in good agreement with the value determined from the hysteresis loops on the basis of the S–W model. Our work suggests that the magneto-optical Kerr effect susceptometer can be employed to determine the magnetic anisotropy constant accurately.

References

[1] Heinrich B and Bland J A C 2004 *Ultrathin Magnetic Structures* (Berlin: Springer-Verlag)
[2] Shiratsuchi Y, Yamamoto M and Bader S D 2007 *Prog. Surf. Sci.* **82** 121
[3] Mermin N D and Wagner H 1966 *Phys. Rev. Lett.* **17** 1133
[4] Bander M and Mills D L 1988 *Phys. Rev. B* **38** 16
[5] Wang S X, Sun N X, Yamaguchi M and Yabukami S 2000 *Nature* **407** 150
[6] Snoek J L 1947 *Nature* **160** 90
[7] Žutić I, Fabian J and Das Sarma S 2004 *Rev. Mod. Phys.* **76** 323
[8] Yaegashi S, Kurihara T and Kazuyuki S 1997 *J. Appl. Phys.* **81** 6303
[9] Rezende S M, Moura J A S and de Aguiar F M 1994 *Phys. Rev. B* **49** 15105
[10] Mattheis R and Quednau G 1999 *J. Magn. Magn. Mater.* **205** 143
[11] Garreau G, Hajjar S, Bubendorff J L and Pirri C 2005 *Phys. Rev. B* **71** 094430
[12] McGuire T and Potter R I 1975 *IEEE Transactions on Magnetics* **11** 1018
[13] Dahlberg D E 1988 *J. Appl. Phys.* **63** 4270
[14] Miller B H andDahlberg E D 1966 *Appl. Phys. Lett.* **69** 3932
[15] Cao W N, Li J, Chen G, Zhu J, Hu C R and Wu Y Z 2011 *Appl. Phys. Lett.* **98** 262506
[16] Li J, Jin E, Son H, Tan A, Cao W N, Hwang C and Qiu Z Q 2013 *Rev. Sci. Instrum.* **83** 033906
[17] Gruyters M 2006 *Phys. Rev. B* **73** 014404
[18] Ye J, He W, Wu Q, Liu H L, Zhang X Q, Chen Z Y and Cheng Z H (unpublished)
[19] Arnold C S, Dunlavy M and Venus D 1997 *Rev. Sci. Instrum.* **68** 4212
[20] Falkowski M, Kowalczyk A and Tolinski T 2013 *J. Magn. Magn. Mater.* **331** 144
[21] Shang Y M and Yao K L 2005 *Chin. Phys. Lett.* **22** 195
[22] Kataja M and van Dijken S 2011 *Rev. Sci. Instrum.* **82** 103901
[23] Poulopoulos P, Farle M, Bovensiepen U and Baberschke K 1997 *Phys. Rev. B* **55** 18
[24] Rodríguez-Suárez R L, Vilela Leão L H, de Aguiar F M, Rezende S M and Azevedo A 2003 *J. Appl. Phys.* **94** 4544
[25] Li Y L, Feng T F, Chen Q, Huang A P and Chen Z Y 2011 *Materials Letters* **65** 2589
[26] Kipgen L, Fulara H, Raju M and Chaudhary S 2012 *J. Magn. Magn. Mater.* **324** 3118
[27] Yun G H, Bai Y H and Narsu B 2009 *Acta Phys. Sin.* **58** 4962 (in Chinese)
[28] Ma Q, Jiang J J, Bie S W, Tian B, Liang P and He H H 2009 *Chin. Phys. B* **18** 2063