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Magnetization reversal of Fe ultrathin film on Cu(100)*

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The magnetization reversal of Fe/Cu(100) ultrathin films grown at room temperature is investigated by using an *in situ* magneto-optical Kerr effect polarimeter with a magnet that can rotate in a plane of incidence. There occur spin reorientation transitions from out-of-plane to in-plane magnetizations in 8 and 12 monolayers (ML) thick iron films. The coercive fields are observed to be proportional to the reciprocal of the cosine with respect to the easy axis, suggesting that the domain-wall displacement plays a main role in the magnetization reversal process.

Keywords: molecular beam epitaxy, surface magnetism, spins reorientation transition, Kerr effect
PACC: 7560E, 7530T, 7820L

Owing to the potential novel applications in magnetic-storage technology, the magnetization reversal process of ferromagnetic ultrathin films has aroused considerable interest recently. The magnetization reversal in magnetic thin films is strongly affected by magnetic anisotropy.[1,2] In a widely studied system of Fe/Cu(100) ultrathin film, it is well known that the easy direction of magnetization is governed by the competition between surface perpendicular magnetic anisotropy and planar shape magnetic anisotropy. There occurs a spin reorientation transition (SRT), i.e. a transition from an out-of-plane to an in-plane easy magnetization direction, at a specific film thickness $t_{\rm SR}$ and/or a specific temperature $T_{\rm SR}$.[3] Previous investigation has indicated that in the system of Fe/Cu(100) ultrathin film, the growth temperature can affect the spin reorientation behaviour.[4−10] The values of specific film thickness $t_{\rm SR}$ are about 11 and 4–6 ML for Fe/Cu(100) ultrathin films deposited at room-temperature and low temperatures (below 200 K), respectively.[5,7,8] In the vicinity of SRT, the magnetic anisotropies are rather small, which results in a complicated magnetic domain structure. The domain transformations in Fe/Cu(100) ultrathin films under different external fields were investigated by using an ultrahigh vacuum (UHV) Kerr microscope and a scanning near-field optical microscope (SNOM).[5,6] By using the microscopes the domain nucleation and the motion of domain wall were observed and two coexisting spin configurations were found to occur in a narrow thick range in the vicinity of SRT.[5] The formations of stripe domain and pinning stripe domain were also discussed in detail based on the Kerr-microscope images and SEMPA images.[6,11] In order to understand the complex process due to the change of magnetic anisotropy during the SRT, we will discuss the magnetization reversal of Fe/Cu(100) ultrathin film in the vicinity of SRT on the basis of a series of Kerr loops with an external magnetic field along applied different directions in a plane of incidence plane.

The experiments were performed with a combined molecular beam epitaxy (MBE)/scanning tunnelling microscope (STM) system in UHV at a base pressure of about 1×10^{-8} Pa. The substrate was commercial single crystal Cu(100) wafer (MaTeck). In order to achieve a clean Cu(100) surface, the substrate was cleaned by cycles of Ar-ion gun sputtering and annealing at 900 K until sharp (1×1) low energy electron diffraction (LEED) pattern and clean Auger electron spectrum (AES) were obtained. Iron deposition was performed by thermal evaporation from a Knudsen cell while the substrate was kept at room temperature. The amount of the iron deposition was controlled by the temperature of source and the time of deposition, which was calibrated by STM. An *in situ* surface magneto-optical Kerr effect (SMOKE) polarimeter was employed to investigate the magnetic

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properties of the ultrathin Fe films at 120 K. For the SMOKE measurements, the incident angle of the laser beam with a wavelength $\lambda = 632.8$ nm was about 45° with respect to the normal of sample surface. The magnet can be rotated to different directions corresponding to different values of angle, θ. In this paper θ is defined as the direction which respect to the normal of sample surface at the plane of incidence. The magnetic fields were varied from +32 to –32 kA/m in the directions corresponding to different values of angle θ with respect to the normal of sample surface.

Figure 1 shows the Kerr magnetization loops of Fe/Cu(100) films with the values of thickness t being 4, 8 and 12 ML both in polar and longitudinal geometries collected at 120 K. For the samples with the thicknesses of 4 and 8 ML, the perpendicular magnetic anisotropy is evidently indicated by the square hysteresis loops with a full remanence in the polar geometry but no hysteresis loops are displayed in the

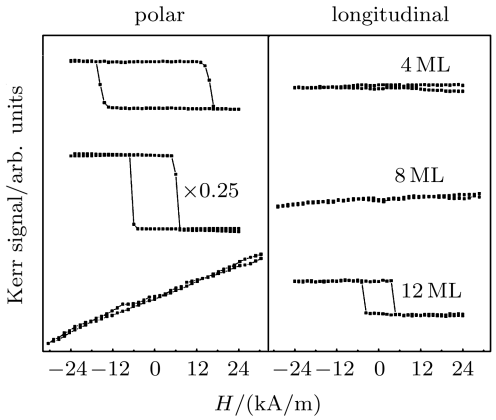


Fig.1. The polar and the longitudinal Kerr signals measured at 120 K for Fe/Cu(100) film at thicknesses of 4, 8 and 12 ML.

longitudinal geometry. In contrast to what are for $t = 4$ and 8 ML, the easy axis of magnetization is changed to in-plane for $t = 12$ ML. In an ultrathin film system, the effective magnetic anisotropy K_{eff} is generally separated from the volume contribution K_{v} and the surface contribution K_{s}. Therefore,

$$K_{\text{eff}} = K_{\text{v}} + 2K_{\text{s}}/d, \tag{1}$$

where d is the thickness of iron film and the factor 2 is due to the fact that one film has two surfaces. The effects of K_{v} and K_{s} make easy axis of magnetization favourable for in-plane and out-of-plane, respectively. When K_{eff} is positive the magnetization is perpendicular to the film plane. The perpendicular magnetic anisotropy in iron ultrathin films ($d \leq 8$ ML) results from the contribution mainly coming from surface effect. With the thickness increasing, the contribution of surface anisotropy decreases significantly, and consequently, the planar shape magnetic anisotropy plays a dominant role in determining the overall magnetic anisotropy. This result is in agreement with spin reorientation transition from perpendicular to in-plane occurring at thickness of about 11 ML.[8] Since the easy magnetization directions for $t = 8$ and 12 ML are out-of-plane and in-plane, respectively, we choose 8 and 12 ML as the typical thicknesses of Fe/Cu(100) thin films to probe the magnetization reversal process.

In order to understand the magnetization reversal process, the SMOKE hysteresis loops for $t = 8$ ML with various angles of the external magnetic fields are plotted in Fig.2. It is observed that all hysteresis loops show full remanence with a high coercive squareness. The squareness does not change with angle. When the angle exceeds 80° hysteresis loop does not hold but reduces to a curve, not a complete loop (not shown here), implying that the external magnetic field of 32 kA/m is not strong enough to offset the perpendicular magnetic anisotropy field.

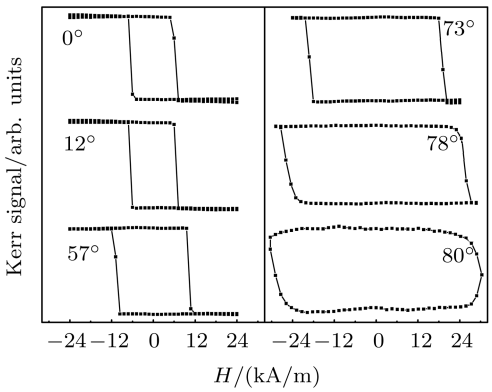


Fig.2. SMOKE hysteresis loops of 8 ML thick iron film for the magnetic field at the various degrees of angle, θ.

The angle dependence of coercivity for $t = 8$ ML is illustrated in Fig.3. Surprisingly, the experimental data of H_{c} increases significantly with the angle increasing, which is completely different from the result obtained from the Stoner–Wolfarth single domain rotation model. The domain expansion plays a dominant role in the magnetization reversal process.[12] According to the theory of domain-wall pining at a local defect, the coercivity will be proportional to the reciprocal of the cosine when domain walls propagate from one domain to another through a local defect.[13]

Owing to the strongly perpendicular surface magnetic anisotropy, we employ a simple model of domain wall pinning in which the magnetization directions of domain have only two options: 0° and 180°. It is adjudged from Fig.1 that there is no or a small longitudinal component to affect the measurement of Kerr signals of 8 ML thick film. When the external field has an angle θ deviating from the normal of surface (the easy axis of perpendicular magnetic anisotropy), the Zeeman energy term is $-MH\cos(\theta)$. Therefore, $H\cos(\theta)$ can be considered as an effective external field that induces the domain growth. If we fit the experimental data H_c to a function of θ with nonlinear regression, the formula of $H_c(\theta) = H_c(0)/\cos(\alpha\theta)$ can be best fitted to experimental data, where $H_c(0) = 6.2\,\mathrm{kA/m}$ and $\alpha = 0.97$ that is a phenomenological fitting parameter.[13] Similar results were also observed in Fe ultrathin films on Si(111) by using an iron silicide template.[14] Therefore, one can conclude that when the applied magnetic field is close to the easy axis, the magnetization is caused by the domain-wall displacement and the coercive field follows the relationship predicted by the domain-wall displacement model.

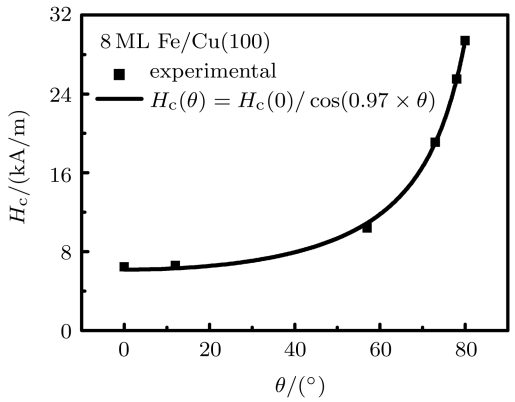


Fig.3. Coercivity of the SMOKE hysteresis measurements versus θ, where the solid line is for a least square fit of the coercivity data to a function of $H_c(\theta) = H_c(0)/\cos(\alpha\theta)$.

The SMOKE hysteresis loops for $t = 12\,\mathrm{ML}$ with an external magnetic field at various angles are plotted in Fig.4. In contrast to the curves of Fe/Cu(100) ultrathin film with $t = 8\,\mathrm{ML}$, the SMOKE hysteresis loops for $t = 12\,\mathrm{ML}$ with an in-plane anisotropy have a square shape with a ramp baseline. Furthermore, the sign of the Kerr signal slope changes from positive to negative when the angle varies from −5° to 15°, in which the external field passes across the easy axis at 90°. The unusual Kerr loops in an ultrathin Fe/Cu(100) film with $t = 12\,\mathrm{ML}$ result from the contributions of two components: polar and longitudinal Kerr signals. Ding *et al*[15,16] have proposed an experimental method to separate the polar Kerr signal from the longitudinal Kerr signal by virtue of the component-resolved Kerr effect. Lee *et al*[17] also developed a method to analyse SRT and magnetization reversal through the full vectorial analysis of the magnetization components. According to the principle of analysing polar and longitudinal Kerr signals, the Kerr signal is proportional to $\cos\left(\dfrac{k \bullet M}{|k|\,|M|}\right)$, where k is the propagation vector of the incident light and M is the vector of the magnetization.[15,18] In our geometry the k is fixed, so the M can be divided into longitudinal magnetization M_x and polar magnetization M_z. From simple calculation, we can draw the conclusion that the Kerr signal will change sign when the direction of the external field passes across its hard axis.

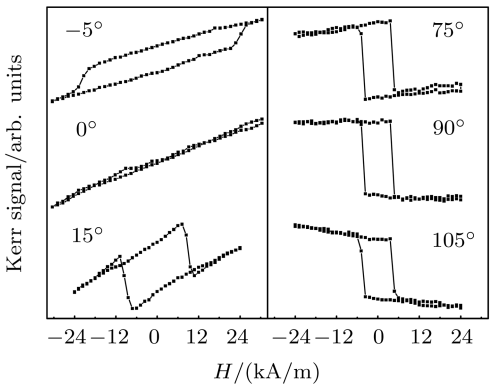


Fig.4. SMOKE hysteresis loops of 12 ML thick iron film for an applied magnetic field at various angles.

We choose a simple but reasonable method to analyse the Kerr curves of 12 ML thick iron film. A typical example is taken to show how to divide the Kerr curve into longitudinal and polar signals (see the insert in Fig.5(a)). The longitudinal curve is square shape and the polar curve is line shape with a slope. In this way, we can analyse the slope of the polar signal and the coercivity of longitudinal signal. Figure 5(a) shows the variation of slope with angle. Its sign changes from positive to negative when the angle varies from less to larger than 90°, which is for the hard axis of polar magnetization. The sign of longitudinal Kerr signal has the same change at the hard axis of in-plane magnetization. The slope of polar signal has a maximum value at 0°, which is for its easy axis. What is more, we know that the Kerr intensity is much stronger in polar MOKE than in longitudinal

MOKE for a given same M.[15] So it is hard to use hysteresis curves to determine the anisotropy, for the scales of M_x and M_z are different.

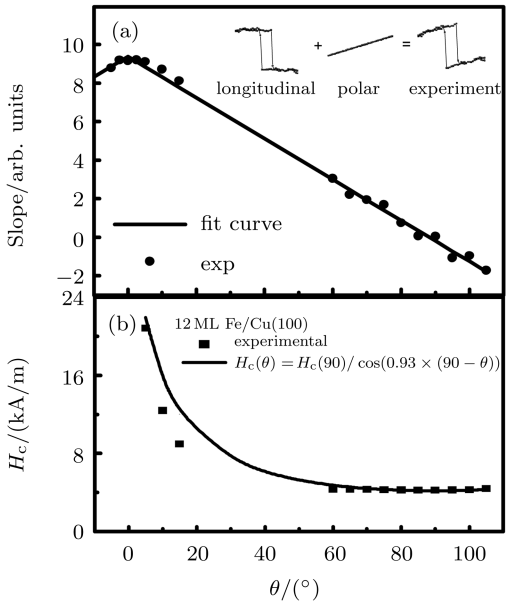


Fig.5. The slope value of polar signal distinguished from the loops of Fig.4 as a function of θ with an insert showing that an experimental hysteresis loop of the 12 ML thick Fe/Cu(100) film at 65° as an example is divided into polar and longitudinal signals (a), and coercivity of 12 ML thick Fe/Cu(100) film as a function of θ, where the solid line represents a fitting curve of the coercivity data to the function of $H_c(\theta) = H_c(90)/\cos(\alpha(\theta - 90))$ (b).

After removing the contribution of polar Kerr signals, the angle dependence of longitudinal Kerr loops is replotted in Fig.6. All longitudinal Kerr loops take

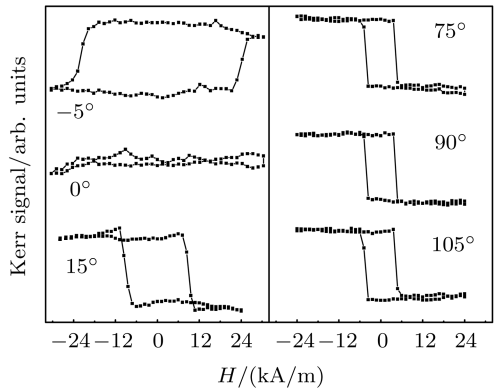


Fig.6. Longitudinal components of SMOKE hysteresis loops of 12 ML thick iron film for an applied magnetic field at various angles.

on square shape, which suggests the in-plane anisotropy of Fe/Cu(100) ultrathin film with t = 12 ML. The relation between coercivity and angle is plotted in Fig.5(b). Since the easy direction of magnetization for the sample with t = 12 ML is in-plane, the angle between the easy magnetization direction and magnetic field should be $90° - \theta$. Again, one can find that the coercive field follows the relation predicted by the domain-wall displacement model, i.e. $H_c(\theta) = H_c(90)/\cos(\alpha(\theta - 90))$, where H_c (90) is 4.2 kA/m, and α is 0.93 (shown in Fig.5(b)). The domain expansion still takes effect in the magnetization reversal process.

Generally, there are two basic models for understanding the angular dependence of the magnetization reversal: coherent rotation and domain-wall nucleation and/or displacement. When the magnetic field is close to the hard axis, the magnetization reversal is caused by the coherent rotation dominantly. When the magnetic field is close to the easy axis, the magnetization reversal is caused by the domain-wall displacement and the coercive field follows the relation predicted by the domain-wall unpinning model. Since an external magnetic field of 32 kA/m is not strong enough to offset the magnetic anisotropy field, the reversible coherent rotation occurs with no hysteresis loop when the magnetic field is close to the hard axis. And consequently, the unpinned domains grow quickly just before the switching field causes an irreversible jump in the hysteresis loops. According to the theory of domain-wall pining at a local defect, the coercivity is proportional to the reciprocal of the cosine when domain walls propagate from one domain to another through a local defect in the process of domain expansion.[6,13] The characters of angular dependence of M-H loops and a reciprocal cosine angle dependence of coercivity clearly evidence the domain wall pinning in magnetization reversal process.

In summary, we have investigated the magnetization reversal of ultrathin Fe/Cu(100) films with the thicknesses of 8 ML with out-of-plane magnetization and 12 ML in-plane magnetization separately before and after spin reorientation transition. We have analysed in detail Kerr curves of iron films at different angles of an external field around a plane of the incidence. Through the evaluation of coercivity we find that the coercivity is proportional to the reciprocal of the cosine with respect to the easy axis both for 8 and 12 ML thick Fe/Cu(100) films. The domain expansion is mainly due to the motion during the magnetization reversal in this system. For a 12 ML thick film the polar signal with a diverging slope is coupling to the longitudinal signal.

References

[1] Johnson M T, Bloemen P J H, den Broeder F J A and De Vries J J 1996 *Rep. Prog. Phys.* **59** 1409

[2] Kooy C and Enz U 1960 *Philips. Res. Rep.* **15** 7

[3] Pappas D P, Kamper K P and Hopster H 1990 *Phys. Rev. Lett.* **64** 3179

[4] Müller S, Bayer P, Reischl C and Heinz K 1995 *Phys. Rev. Lett.* **74** 765

[5] Mentz E, Bauer A, Günther T and Kaindl G 1999 *Phys. Rev.* B **60** 7379

[6] Meyer G, Bauer A, Crecelius T, Mauch I and Kaindl G 2003 *Phys. Rev.* B **68** 212404
Enders A, Repetto D, Peterka D and Kern K 2005 *Phys. Rev.* B **72** 054446

[7] Li D Q, Freitag M, Pearson J, Qiu Z Q and Bader S D 1994 *Phys. Rev. Lett.* **72** 3112

[8] Berger A, Feldmann B, Zillgen H and Wutting M 1998 *J. Magn. Magn. Mater.* **183** 35

[9] Zharnikov M, Dittschar A, Kuch W, Schneider C M and Kirschner J 1996 *Phys. Rev. Lett.* **76** 4620

[10] Enders A, Peterka D, Repetto D, Lin N, Dmitriev A and Kern K 2003 *Phys. Rev. Lett.* **90** 217203

[11] Vaterlaus A, Stamm C, Maier U, Pini M G, Politi P and Pescia D 2000 *Phys. Rev. Lett.* **84** 2247

[12] Zhu J G and Bertram H N 1991 *J. Appl. Phys.* **69** 6084

[13] You C Y, Park S, Lee S and Falco C M 2004 *Phys. Rev.* B **69** 134402

[14] He W, Zhan Q F, Wang D Y, Chen L J, Sun Y and Cheng Z H 2007 *Chin. Phys.* **16** 3541

[15] Ding H F, Pütter S, Oepen H P and Kirschner J 2000 *J. Magn. Magn. Mater.* **212** 5

[16] Ding H F, Pütter S, Oepen H P and Kirschner J 2001 *Phys. Rev.* B **63** 134425

[17] Lee J W, Kim J, Kim S K, Jeong J R and Shin S C 2002 *Phys. Rev.* B **65** 144437

[18] Zak J, Moog E R, Liu C and Bader S D 1991 *Phys. Rev.* B **43** 6423