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Magnetization reversal of ultrathin Fe film grown on Si(111) using iron silicide template*

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Ultrathin Fe films were epitaxially grown on Si(111) by using an ultrathin iron silicide film with $p(2 \times 2)$ surface reconstruction as a template. The surface structure and magnetic properties were investigated *in situ* by low energy electron diffraction (LEED), scanning tunnelling microscopy (STM), and surface magneto-optical effect (SMOKE). Polar SMOKE hysteresis loops demonstrate that the Fe ultrathin films with thickness $t < 6$ ML (monolayers) exhibit perpendicular magnetic anisotropy. The characters of M–H loops with the external magnetic field at difference angles and the angular dependence of coercivity suggest that the domain-wall pinning plays a dominant role in the magnetization reversal process.

Keywords: molecular beam epitaxy, surface magnetism, magnetization reversal, Kerr effect
PACC: 7560, 7560E, 7530T, 7820L

The epitaxial growth and magnetic properties of ferromagnetic transition metal films on Si substrate have attracted much attention due to their importance in the fundamental research and application potential in spintronic devices.[1] Unfortunately, common 3d ferromagnetic metal, such as Fe, easily reacts with Si to form various stoichiometries of $Fe_{1-x}Si_x$ alloys and produces a rough Fe/Si interface.[2,3] Therefore, it is very difficult to grow epitaxially Fe ultrathin film on Si(111) surface with atomically flatness for investigations of its low-dimensional magnetic properties. In order to prevent the interdiffusion of Si and Fe, some attempts have been performed by inserting a thin buffer layer of Au,[3] Cu,[4] GaSe[5] or CaF_2.[6] However, the roughness of the inserted buffer layer influences significantly on the onset of magnetization.[3] A recent work has demonstrated that the epitaxial growth of Fe films on Si(111) can be achieved by using an ultrathin iron silicide template.[7] Although the onset of ferromagnetism and magnetic anisotropy have been investigated by conventional polar and longitudinal surface magneto-optical Kerr effect (SMOKE) and transverse-biased initial inverse susceptibility and torque measurements, the magnetization reversal process are not yet well understood. Furthermore, the effect of cap layer Ge with the thickness of 5 nm on the magnetic properties cannot be ignored. In the present research, we have investigated the magnetic properties of $Fe/FeSi_2/Si(111)$ system without cap layer by means of *in situ* SMOKE. The magnetization reversal of Fe ultrathin film is discussed in term of angle dependence of coercivity.

The experiments were performed with a combined molecular beam epitaxy (MBE)/scanning tunnelling microscope (STM) system in ultrahigh vacuum (UHV) at a base pressure of about 1×10^{-8} Pa. The substrates were commercial n-type Si(111) wafers (phosphor doped, $\sim 3\,\Omega \cdot$cm). In order to achieve a clean Si(111) surface, the substrate was degassed at 1000 K for several hours, and then repeatedly flashed at 1500 K until a high quality 7×7 surface reconstruction was observed by OMICRON variable temperature STM as well as shown by the appearance of sharp low-energy-electron-diffraction (LEED) pattern. Iron deposition was performed by thermal evaporation from a Knudsen cell at a rate of 0.1 ML/min. (1 ML = 7.88×10^{14} atom/cm^2 for Si(111) plane) while the substrate was kept at room temperature. All room-temperature STM images reported here were recorded in the constant-current mode. A chemically etched tungsten tip was used as the STM probe. The LEED patterns were collected at normal incidence with a

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four-grid optics. The magnetic properties were investigated *in-situ* by SMOKE in polar and longitudinal geometries from 120 K to 300 K. For the SMOKE measurements, the incidence angle of the laser beam of wavelength $\lambda = 632.8$ nm was about 45° with respect to the sample surface normal. The Magnetic field of $+3.2 \times 10^4$ to -3.2×10^4 A/m was applied at different angles θ with respect to the sample surface normal.

In order to obtain high quality epitaxial iron silicide template by solid phase epitaxy on Si(111) substrate, 2 ML Fe was preliminarily deposited on the substrate at room temperature and annealed at 800 K for several minutes by direct heating. At the completion of reaction between Fe and Si, an atomically flat iron silicide ultrathin film with large area was formed, as observed by STM (Fig.1(a)). Atomic resolution STM image (Insert of Fig.1(a)) and sharp LEED pattern (Fig.1(b)) indicate that the atomic ordering is $p(2\times2)$ reconstructed phase. Finally, Fe was deposited on the iron silicide template. STM topographic image shows that Fe atoms aggregate immediately into three-dimensional (3D) islands indicating the typical Volmer–Weber growth mode (Fig.1(c)). The LEED pattern indicates that three-fold symmetry still exists even for a thickness reaching 5.4 ML (Fig.1(d)).

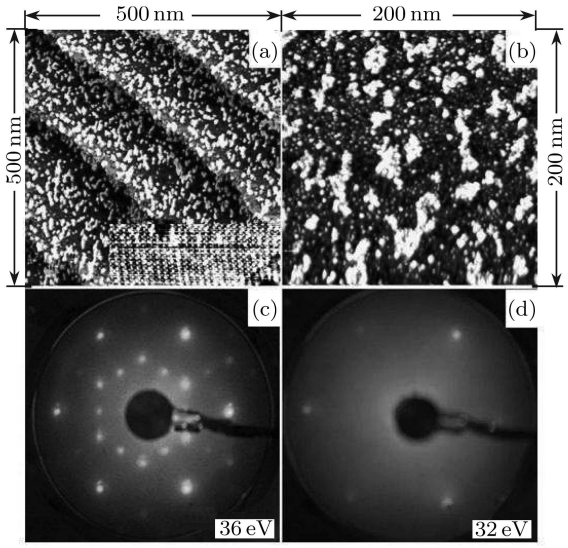


Fig.1. (a) STM topographic image (500 nm × 500 nm) of 2ML of Fe after annealing at 800 K. Insert shows the high resolution image. (b) STM image (200 nm × 200 nm) of nominal 5.4 ML Fe film grown on the template. (c) LEED pattern of iron silicide at 36 eV and (d) LEED pattern of 5.4 ML Fe at 32 eV.

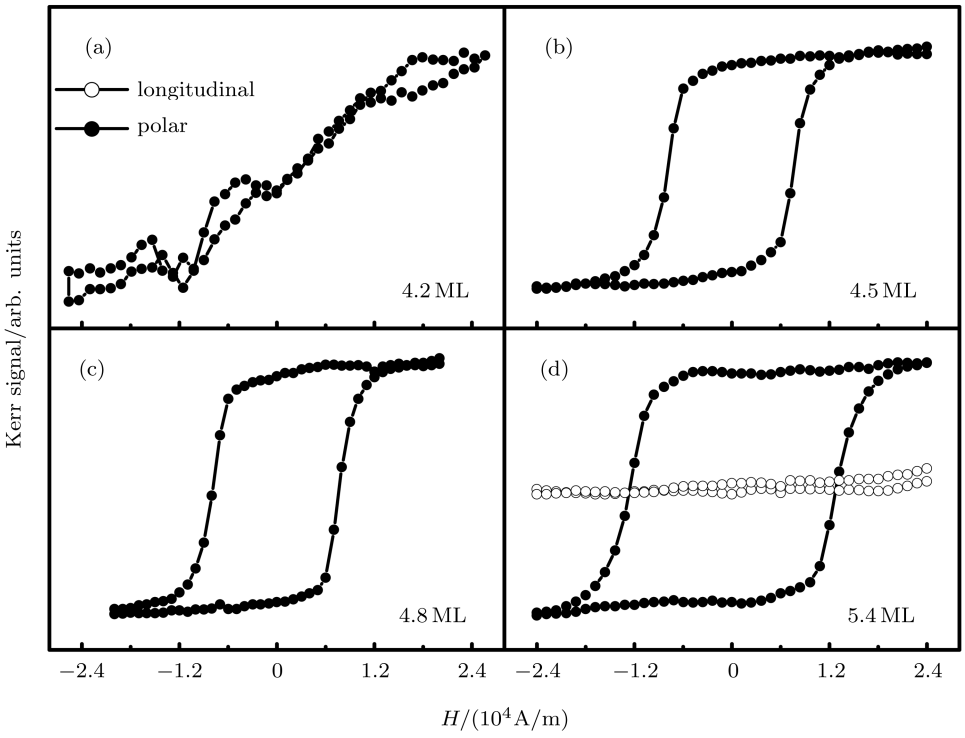


Fig.2. A series of Magnetization Kerr loops at 120 K in polar geometry at different Fe thickness: (a) 4.2 ML (b) 4.5 ML and (c) 4.8 ML (d) The loops of 5.4 ML in polar (full circle) and longitudinal (empty circle) geometries.

To investigate the presence of ferromagnetic order and the magnetic anisotropy, the Kerr magnetization loops both in polar and longitudinal geometries were collected at 120 K. Hysteresis loop was not detected for the films with nominal thickness below 4.2 ML (Fig.2(a)). The perpendicular magnetic anisotropy is evidenced for samples with coverage from 4.5 to 5.4 ML by the square hysteresis loops with full remanence in the polar geometry and no hysteresis loops in the longitudinal geometry (Figs.2(b)–(d)). In ultrathin film systems, the effective magnetic anisotropy K_{eff} is generally separated into 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 comes from that the film has two surfaces. The effect of K_{v} and K_{s} causes the easy axis of magnetization to favour in-plane and out-of-plane, respectively.[8] When K_{eff} is positive the magnetization is perpendicular to the film plane. The perpendicular magnetic anisotropy in iron ultrathin films ($d < 6$ ML) is the result of the contribution mainly coming from surface effect. With increasing thickness, the contribution of surface anisotropy decrease, significantly, and consequently, the planar magnetic anisotropy plays a dominant role in determining the overall magnetic anisotropy. Previous investigation also indicated that the system of $Fe/FeSi_2/Si(111)$ has a spin-reorientation transition at 6 ML.[7]

In order to gain insight into the magnetization reversal process, SMOKE hysteresis loops at 150 K with various angles of the magnetic field with respect to the sample surface normal were plotted in Fig.3. It was observed that all hysteresis loops show full remanence with low coercivity. The squareness does not change with angles, implying that the external magnetic field of 3.2×10^4 A/m is not strong enough to overcome the perpendicular magnetic anisotropy field.

The angular dependence of coercivity is illustrated in Fig.4. Surprisingly, the experimental data of H_{c} increases significantly with increasing angle, which is completely different from the prediction on the basis of the Stoner–Wolfarth single domain rotation model.[9] It was known that the magnetization reversal process is not only determined by domain rotation, but also by the domain-wall displacement. The

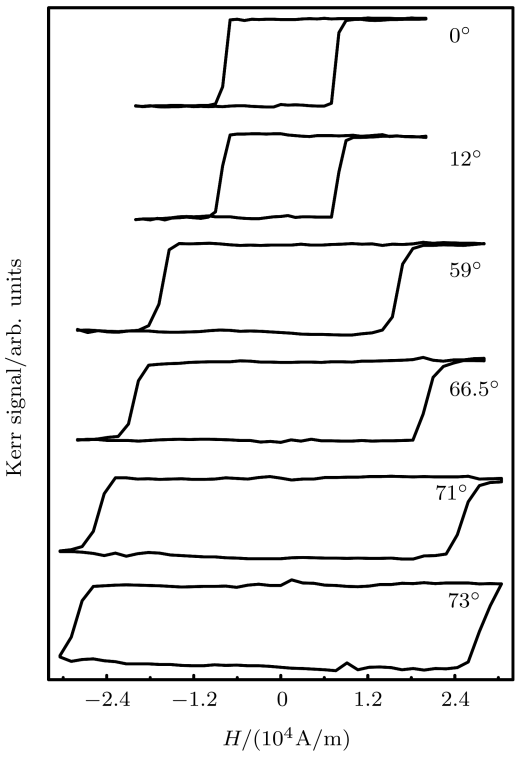


Fig.3. SMOKE hysteresis loops at 150 K for various angles θ of the magnetic field.

hysteresis curves of 5.4 ML iron films exhibit high squareness and large size jumps, implying that the domain expansion plays a dominant role in the magnetization reversal process.[10] Owing to the strong perpendicular surface magnetic anisotropy, 180° domain walls are expected to exist in this system and the magnetization direction of domain has only two choices: 0° or 180° with respect to the sample surface normal.[11] Consequently, there is no longitudinal component to effect the measurement of Kerr signals. When the external field is deviated at an angle θ from the normal surface, $-\mu_0 MH\cos\theta$ is the Zeeman energy term. $H\cos(\theta)$ can be considered as the effective external field which induced the motion of domain wall. If we fit the experimental data H_{c} with a function of θ with nonlinear regression, the formula of $H_{\text{c}}(\theta) = H_{\text{c}}(0)/\cos\theta$ can be best fitted to experimental data at $H_{\text{c}}(0) = 8.0 \times 10^3$ A/m. According to the theory of domain-wall pining at a local defect, the coercivity will be proportional to the inverse of the cosine when domain walls propagate from one domain to the other through a local defect.[12–16] Moreover, if we use the $H_{\text{eff}}(\theta) = H\cos\theta$ to replace the H and replot the M–H loops (Insert of Fig.4), all curves have the same saturation field and the sharpness is close to the

loop of $\theta = 0°$. The characters of angular dependence of M–H loops and an inverse cosine angular dependence of coercivity provide a clear evidence for domain wall pinning in magnetization reversal process. In the $Fe/FeSi_2/Si(111)$ system the defects consists of the nonmagnetic Si atoms emerging through the diffusion of interface or the disfigurement by the strain in the epitaxial thin films.

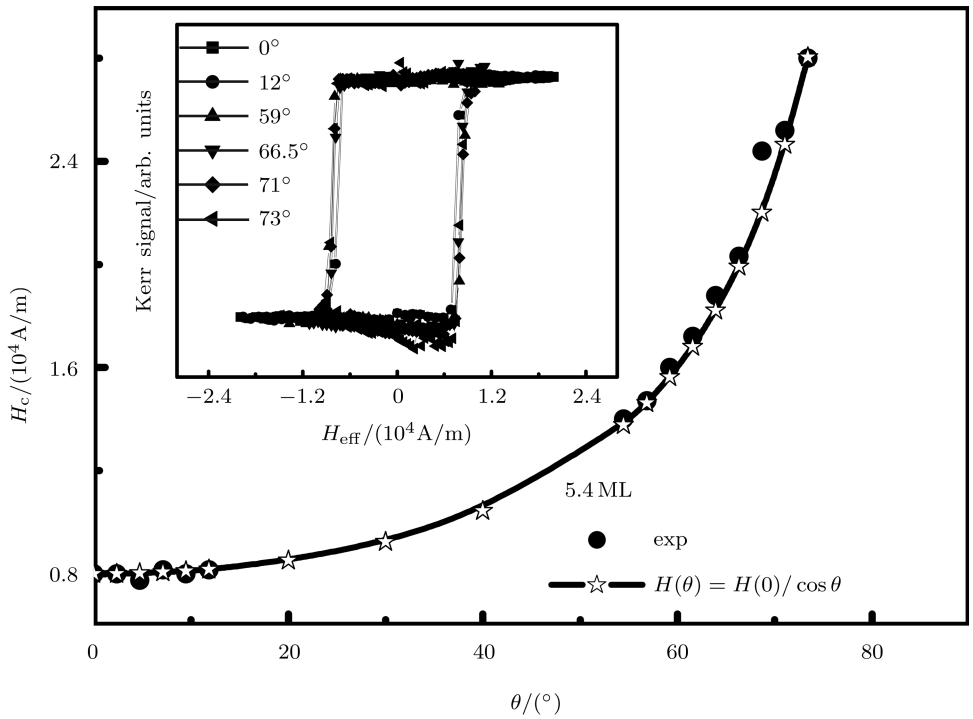


Fig.4. Coercivity of the SMOKE hysteresis measurements as a function of θ from 0° to 90°. The solid curve is a least square fit to the coercivity data of the function $H_{\rm c}(\theta) = H_{\rm c}(0)/\cos\theta$. Insert: SMOKE hysteresis loops for various angles θ of the effective external magnetic field $H_{\rm eff}(\theta) = H\cos\theta$.

In summary, the ultrathin Fe films grown on Si(111) by using an ultrathin iron silicide film as a template exhibit strong perpendicular magnetic anisotropy when the thickness is below 6ML. An inverse cosine angular dependence of coercivity suggests that the domain-wall pinning plays a dominant role in magnetization reversal process.

References

[1] Zutic I, Fabian J and Sarma S D 2004 *Rev. Mod. Phys.* **76** 323

[2] Gallego J M, García J M, Alvarvz J and Miranda R 1992 *Phys. Rev.* B **46** 13339

[3] Zavaliche F, Wulhekel W, Xu H and Kirschner J 2000 *J. Appl. Phys.* **88** 5289

[4] Castrucci P, Gunnella R, Bernardini R, Falcioni P and de Crescenzi M 2002 *Phys. Rev.* B **65** 235435

[5] Eddrief M, Yang Y, Etgens V H, Mosca D H, Maurice J L, George J M, Fert A and Bourgognon C 2001 *Phys. Rev.* B **63** 094428

[6] Heim K R, Hembree G G and Scheinfein M R 1994 *J. Appl. Phys.* **76** 8105

[7] Garreau G, Hajjar S, Bubendorff J L, Pirri C, Berling D, Mehdaoui A, Stephan R, Wetzel P, Gewinner G, Boukari S and Beaurepaire E 2005 *Phys. Rev.* B **71** 94430

[8] Qiu Z Q and Bader S D 2000 *Rev. Sci. Instrum.* **71** 1243

[9] Coffey R K, Thomson T and Thiele J U 2002 *J. Appl. Phys.* **92** 4553

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

[11] Lyberatos A 2000 *J. Phys.* D: *Appl. Phys.* **33** R117

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

[13] Zhang H W, Rong C B, Zhang J, Zhang S Y and Shen B G 2003 *Acta Phys. Sin.* **52** 722 (in Chinese)

[14] Liu G J, Shen B G, Sun J R, Wang D J, Xiong C M and Zhang H W 2005 *Chin. Phys.* **14** 604

[15] He K 2006 *Chin. Phys.* **15** 449

[16] Chen Y Z, He S L, Zhang H W, Chen R J, Rong C B, Sun J R and Shen B G 2005 *Acta Phys. Sin.* **54** 5890 (in Chinese)