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Investigation of the magnetic domain structure of (PtCoPt)/Si multilayers by magnetic force microscopy*

Zhang Zhen-Rong(张臻蓉)[a)†], Liu Hong(刘 洪)[b)], and Han Bao-Shan(韩宝善)[a)]

[a)] *State Key Laboratory for Magnetism, Institute of Physics, Chinese Academy of Sciences, Beijing* 100080, *China*

[b)] *Department of Physics, Capital Normal University, Beijing* 100037, *China*

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The domain structure of (PtCoPt)/Si multilayers in the dc demagnetized state has been investigated by magnetic force microscopy. The domain structure is found to change dramatically as the thickness of the non-magnetic Si sublayer (t_{Si}) increases. Together with the analysis of magnetic properties, the variation of the domain period indicates that the domain wall energy decreases. Using the model developed by Draaisma and de Jonge, the domain wall energy is obtained.

Keywords: magnetic force microscopy, multilayers, domain structure
PACC: 0779, 4280X, 7570K

1. Introduction

Because of the significant practical implications, the domain structure in thin and ultrathin ferromagnetic films has been the object of vigorous experimental and theoretical investigation. A special group of interest among these is arrays of domains with their magnetization perpendicular to the surface of the specimen. Magnetic force microscopy (MFM) has made possible the investigation of surface magnetic microstructures down to 50nm.[1]

Pt/Co multilayers have been actively studied for next generation magnetic-optical recording media owning to their increased polar Kerr rotation at shorter wavelength and the presence of remnant perpendicular magnetic anisotropy.[2,3] Efforts are therefore being made to improve other magneto-optic recording properties such as the magnetic coercivity and crystalline anisotropy. These efforts have involved increasing the thickness of the Co or Pt layers and using a binary alloy rather than a single metal as the spacer layer, such as PtCu(Al)/Co, PdCu/Co.[4–7] Recently, some reports of (PtCoPt)/Ni multilayers have encouraged us to investigate the influence of the non-magnetic Si sublayer on the properties of (PtCoPt)/Si multilayers.[8,9]

In this paper, we have studied by MFM the magnetic domain structure of sputtered (PtCoPt)/Si multilayers by increasing the thickness of the Si sublayer (t_{Si}) in their dc demagnetized state. The domain structure was interpreted in terms of micromagnetic theory.

2. Experiment

The multilayer films of (PtCoPt)/Si (t_{Si}=0–0.8nm) were deposited on glass substrate by magnetron sputtering with Ar gas at 0.5Pa, while the substrate holder was cooled by water. All (PtCoPt)/Si multilayer samples were grown on a 45nm thick Pt buffer layer. During the growth, the thicknesses of Pt, Si and Co layers were controlled by sputtering time through a preset computer program with fixed sputtering parameters. And the thickness of Pt and Co layers were kept at 0.45 and 0.24nm for all samples. There were twenty modulation periods of the sample.

The structure of the samples was analysed by small and large angle x-ray diffraction (XRD). The effective perpendicular anisotropy constant $K_{u\,\mathrm{eff}}$ was determined by a magnetic torquemeter (model TRT TOEI). The magnetic properties were characterized by an alternating gradient force magnetometer (AGM). The MFM measurements were realized using a commercial Nanoscope IIIa-D3000 scanning probe microscope from digital instruments.[10] A 15μm tip

*Project supported by the National Natural Science Foundation of China (Grant No 10074081).
†Author to whom correspondence should be addressed: Zhangzr@g203.iphy.ac.cn Fax:(86)-10-82649485 Phone:(86)-10-82649248

covered with a CoCr alloy at the end of a 225μm cantilever scanned the surface and sensed the microscopic forces. We used the tapping/lift mode, which is a non-contact mode but where the tip is allowed to partially fit the surface. The cantilever is driven near its resonance frequency and the force gradient due to the interaction between the tip and the surface changes the resonance frequency that is detected by its amplitude variation with an optical system. Prior to imaging the tip was magnetized perpendicularly to the sample surface.

3. Results and discussion

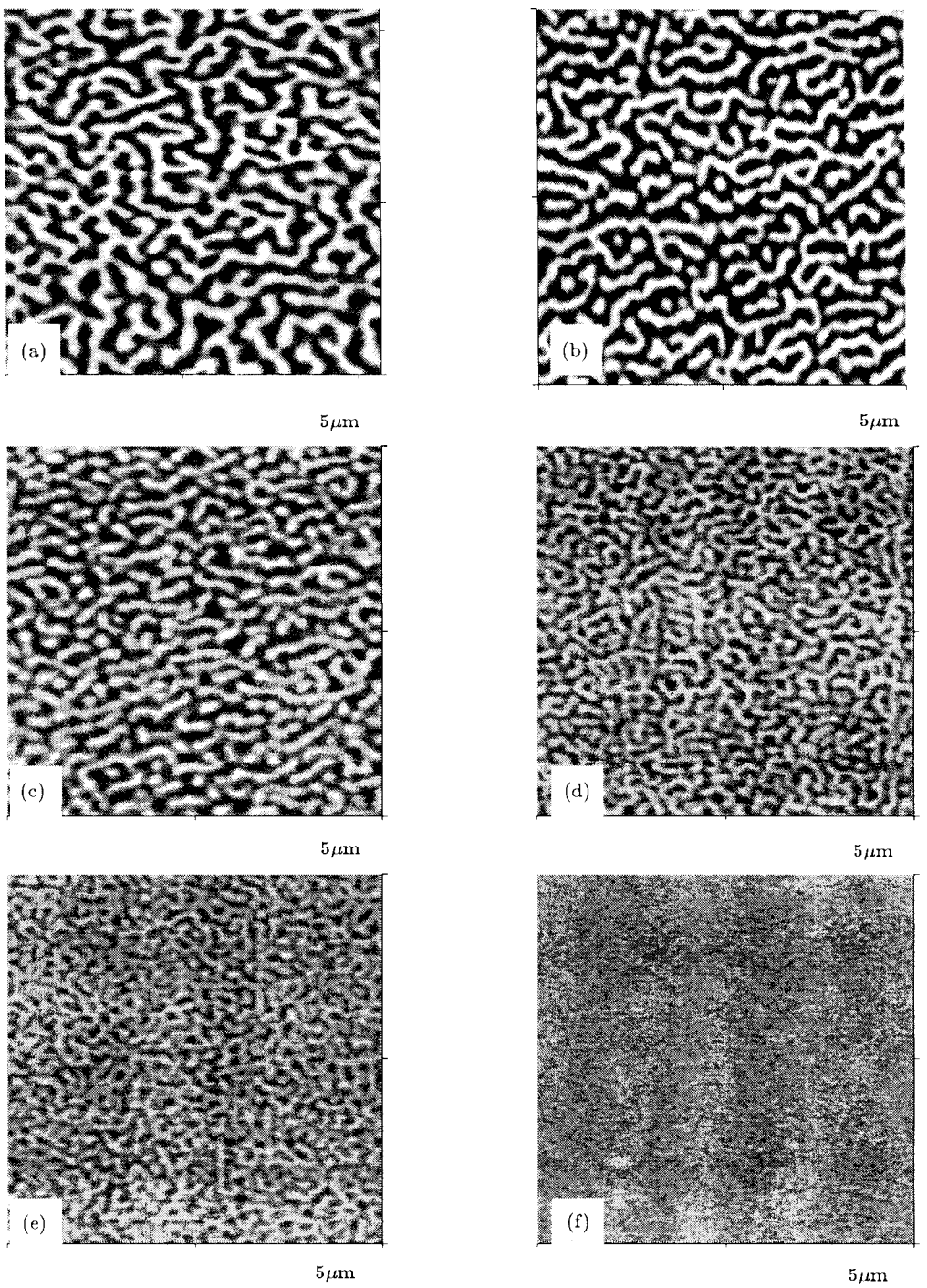


Fig.1. The magnetic force images of the dc demagnetized multilayers with increasing thickness of Si sublayer t_{Si}: (a) 0nm; (b) 0.08nm; (c) 0.16nm; (d) 0.32nm; (e) 0.48nm; (f) 0.80nm.

The small-angle XRD of all samples showed peaks typical of the layered structure. With increasing Si layer thickness, the first-order peak shifts gradually to the low angle side, attributed to the increase of the modulation period length. The intensities of the peaks become weaker and disappear completely when t_{Si}=0.8nm. It is known that the intensities of the small-angle XRD peaks represent the sharpness of the interfaces. The stronger the intensities, the sharper the interfaces. Thus the weakness of the peaks indicates a strong intermixing of atoms at the interfaces. Large-angle x-ray diffraction exhibits a strong Pt (111) peak showing the strong (111) Pt buffer layer and the PtCo (111) peak.

The magnetic force images of the dc demagnetized multilayers with the increase of t_{Si} from 0 to 0.8nm are presented in Fig.1. For pure Pt/Co multilayers (t_{Si}=0nm), the domain pattern is a stripe domain structure with large magnetic contrast between dark and bright domains (Fig.1(a)). This implies that the film has a uniaxial perpendicular anisotropy in which the magnetization is oriented either into or out of the plane. With a thin Si sublayer (t_{Si} =0.08nm) doped in Pt spacer layers, no obvious contrast change is observed and the domain period decreases from 325 to 297 nm. (The domain period was measured from section analyses by average peak-to-peak distance for different directions over the scanned area.) Then the image contrast and the domain period decreased dramatically as t_{Si} increased from 0.16 to 0.48nm (Figs.1(c)–(e)). With a further increase of thickness of the Si sublayer (t_{Si}=0.8nm), no domains are observed (Fig.1(f)).

For the magnetic images in Fig.1, Fig.2(a) displays the root-mean-square (rms) values of the phase shift ($\Delta\varphi$) as a function of t_{Si}. It can be seen that with the increase of t_{Si}, $\Delta\varphi$ decreases. During MFM experiments, $\Delta\varphi$ of the tip oscillation is directly proportional to the second derivative of the vertical component H_z of the sample stray field.[11] Therefore, generally, the measurements of average phase shift $\Delta\varphi$ will give an indication of the effective magnetic moment of the sample.[12] But, in our experiment, when the non-magnetic Si sublayers intercalated, the distance between the magnetic Co sublayers and the tip increased. As is well known, H is given as

$$H(r) = \int_{\text{sample}} \frac{3\hat{n}\cdot[\hat{n}m_2(r_2)] - m_2(r_2)}{r^3} \mathrm{d}V', \quad (1)$$

where r is the observer point outside the sample, $m_2(r_2)$ is the magnetization of the volume element $\mathrm{d}V'$ in the sample and $\hat{n} = r/|r|$. It can be seen that H will decease significantly when the distance between the tip and the sample increases. Then it is reasonable that $\Delta\varphi$ decreases, even though the thickness of the magnetic Co sublayers remains constant. The curve of the average domain period d versus t_{Si} is also presented in Fig.2(b). It shows that the domain period decreases as t_{Si} increases.

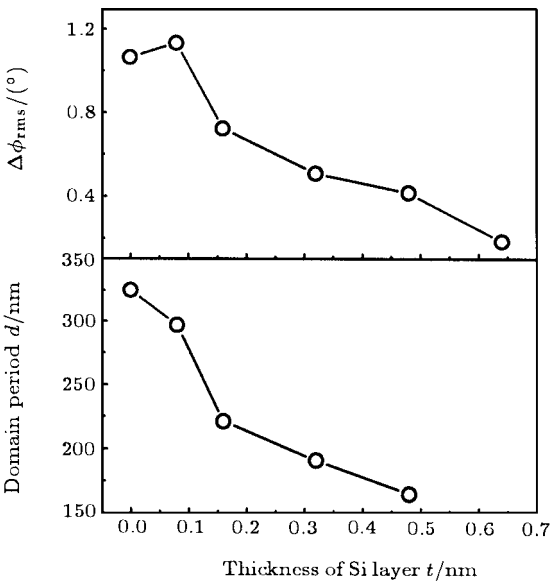


Fig.2. The rms values of the phase shift ($\Delta\varphi$) (a) and the average domain period d (b) corresponding to Fig.1 as a function of the thickness of the Si sublayer t_{Si}.

It is well known that the domain size structure results from a competition between magnetostatic energy and the domain wall energy. Indeed, the magnetostatic energy favours a small domain size in the case of perpendicular magnetization while the energy generated by the creation of domain walls tends to enlarge the domains.

The saturation magnetization was mainly attributed to the Co atoms and adjacent polarized Pt atoms. Since the thickness of Co and Pt layers do not change, M_s per unit Co should be almost constant. The results of AGM show that M_s almost does not change indeed while the thickness of the Si sublayer increases from 0 to 0.8nm. However, the Si thickness increases in our samples, so the saturation magnetization per unit volume will decrease, and in turn the demagnetization energy will decrease. If the domain wall energy does not change, the domain size should be larger. However, the domain size decreases instead. Therefore, the narrower domains indicate that the domain wall energy decreases.

A key quantity for understanding the micromagnetic properties of magnetic film is the domain wall energy σ_w. Draaisma and de Jonge,[13] have modelled the competition between magnetostatic energy and the domain wall energy for perpendicularly oriented multilayer films. In this model, the domains are parallel and the domain walls are at the same lateral positions in all layers. If attention is restricted to films in their ac demagnetized state, the magnetic energy contains two terms: the magnetostatic or demagnetizing energy e_d and the wall energy e_w of the domain walls between neighbouring domains. The demagnetizing energy e_d can be expressed as

$$e_d = \frac{E_d}{\frac{1}{2}\mu_0 M_s^2} = m^2 + \sum_{n=1}^{\infty} \frac{4}{(n\pi)^3} \frac{d}{t} \sin^2\left[\frac{1}{2}\pi n(m+1)\right] f_n(d)$$

with

$$f_n = 1 - \exp\left(-2\pi n \frac{t}{d}\right) + \frac{\sinh^2[\pi n(t/d)]}{\sinh^2[\pi n(D/d)]} \times \left\{\left[1 - \exp\left(-2\pi n \frac{ND}{d}\right)\right] - \left[1 - \exp\left(-2\pi n \frac{D}{d}\right)\right]\right\},$$

where s and t represent the thickness of Co layer and the thickness of nonmagnetic layer, respectively, $D = s + t$ and m=0 for the as-grown state. The domain wall energy e_w per unit area of a domain wall is

$$e_w = \frac{E_w}{\frac{1}{2}\mu_0 M_s^2} = \frac{2\sigma_w}{d\left(\frac{1}{2}\mu_0 M_s^2\right)} = \frac{2\tau}{d},$$

in which

$$\tau = \sigma_w \Big/ \frac{1}{2}\mu_0 M_s^2 \tag{2}$$

is a characteristic length representing the domain wall energy.

By minimizing the total energy density with respect to the domain repetition period d, the following expression can by obtained[13]

$$d = [2\tau/(\partial e_d/\partial d)]^2. \tag{3}$$

Then, for measured values of d and other film parameters (Co layer thickness, modulation period thickness and the number of modulation periods), the value of τ can be determined by numeric computation of Eq.(3). During the calculation, sublayers Pt and Si were regarded as one non-magnetic layer.

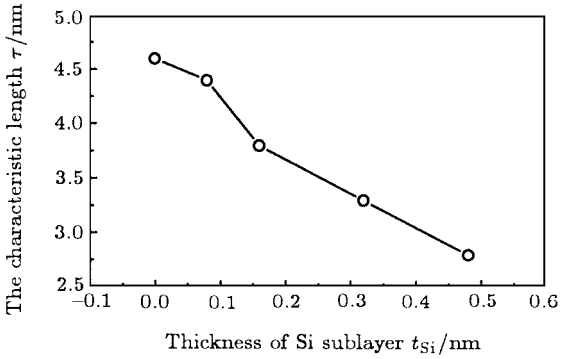


Fig.3. Calculated characteristic length τ, which represents the domain wall energy, plotted as a function of the thickness of the Si sublayer t_{Si}.

Figure 3 gives the calculated value of τ as a function of t_{Si}. It can be seen that with the intercalation of the Si layers, τ decreases. Since the effective saturation magnetization is almost constant, for simplicity, taking M_s of the bulk value of Co (1420kA·m^{-1}) in Eq.(2), we obtained that the domain wall energy σ_w decreases from 9.2 to 5.6mJ·m^{-2} as the t_{Si} changes from 0 to 0.48nm. The values are comparable with the previous reported value of 7.9mJ·m^{-2} by Zeper *et al.*[14]

It is well known that the domain wall energy σ_w is related to effective anisotropy constant $K_{u\,\mathrm{eff}}$ and exchange constant A by the expression

$$\sigma_w = 4\sqrt{AK_{u\,\mathrm{eff}}}. \tag{4}$$

The $K_{u\,\mathrm{eff}}$ value can be obtained through the torque curve by $K_{u\,\mathrm{eff}}$=T_{peak}/V, where T_{peak} is the peak value of torque on the torque curve and V is the volume of the magnetic layer, The measured value of $K_{u\,\mathrm{eff}}$ derived from the magnetic torquemeter is shown in Fig.4. It can be seen that $K_{u\,\mathrm{eff}}$ decreases as t_{Si} increases.

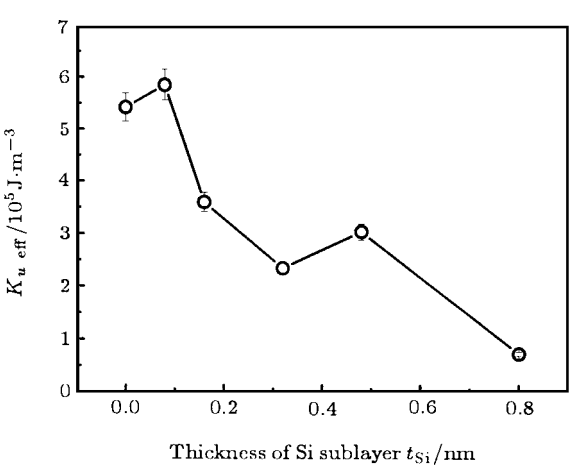


Fig.4. The effective perpendicular anisotropy constant $K_{u\,\mathrm{eff}}$ derived from the magnetic torquemeter as a function of the thickness of the Si sublayer t_{Si}.

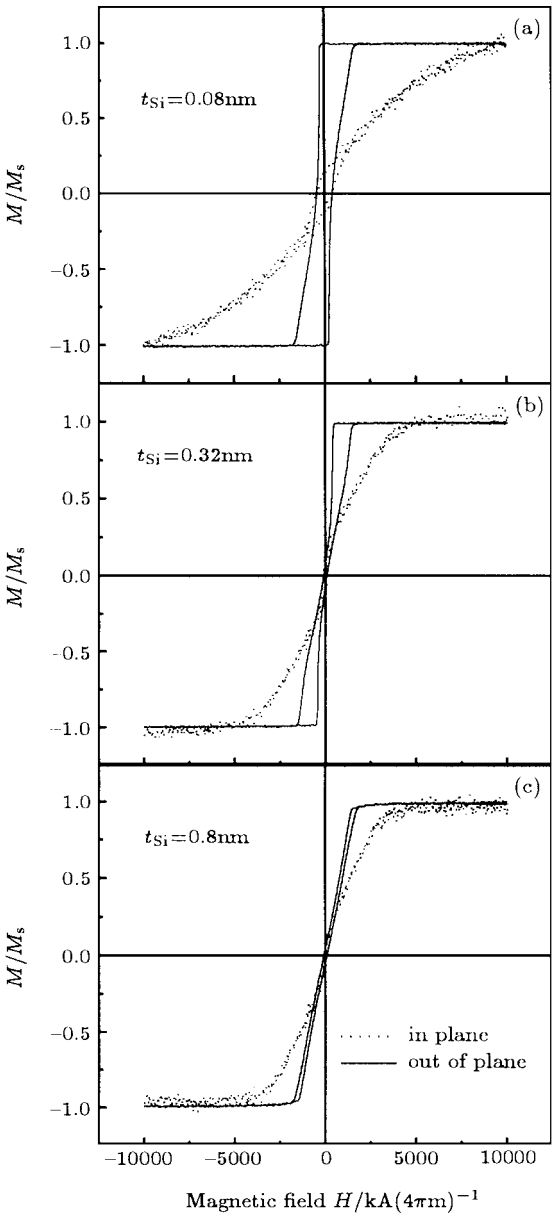


Fig.5. In-plane and out-of-plane hysteresis loops of typical (Pt/Co/Pt)Si samples with decreasing thicknesses of the Si sublayer t_{Si}: (a) 0.08nm; (b) 0.32nm; (c) 0.8nm.

In Fig.5, the typical in-plane and out-of-plane hysteresis loops also show how the perpendicular magnetic anisotropy decreases with increasing Si thickness. As t_{Si} increases, the squareness of the hysteresis loops and coercivity H_c decrease continuously, indicating the decrease of $K_{u\,\mathrm{eff}}$. As for t_{Si}=0.8nm, it can be seen from Fig.4(c) that the perpendicular magnetic anisotropy is very small. The reason that there is no domain observed in the magnetic force image might be that the domain period decreases down to 50nm, the resolution of MFM being about 50nm.[1]

According to Eq.4, calculation shows that the change in the effective perpendicular anisotropy constant should account for the decrease in σ_w. It is known that the perpendicular anisotropy in Co-based multilayer films is, in general, attributed to the interface effect.[15,16] Within a symmetry-based Néel model,[17–19] it can be shown that the anisotropy of the disordered superlattice (K_i) is related to that of the perfect superlattice (K_p) by

$$K_i = \frac{1}{2} K_p \sum_{j=1}^{n} (P_j - P_{j-1})^2,$$

where P_j is the probability of a magnetic atom on layer j. Because of the quadratic dependence on occupancies, small amounts of interdiffusion can result in a large decrease in anisotropy. From small-angle XRD, we know that the intermixing of atoms at the interfaces becomes stronger with increasing Si thickness. Thus, possible interdiffusion of Si atoms into the deeper Pt layer and even Pt/Co interfaces could be expected, which should largely reduce the perpendicular anisotropy. In Co/Au multilayers, the large effect of interface roughness on the interface anisotropy is also found.[20] Brouno also pointed out that roughness always reduces the anisotropy.[21]

4. Conclusions

The magnetic images of the (PtCoPt)/Si multilayers in the dc demagnetized state show that the image contrast and domain period decrease as the thickness of the non-magnetic Si sublayer increases. In addition to the analysis of magnetic properties, the variation of domain period also indicates that the domain wall energy is decreasing. Using the model developed by Draaisma and de Jonge, the domain wall energy was found to decrease from 9.2 to 5.6mJ·m^{-2} as t_{Si} varied from 0 to 0.48nm.

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