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Magnetization Reversal Study of Co Films on Nano-sized Pyramidal Ag Islands

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Nano-sized pyramidal Ag(111) islands on Si(111) substrates were fabricated by using the molecular beam epitaxy technique; a 9 nm Co thin film was then grown onto the Ag films at 100°C. We have experimentally demonstrated that the magnetic behavior of Co films is strongly dependent on the thickness and morphology of the Ag under layer. The Ag film in order to reduce the surface free energy, forms isolated islands with {111} sidewall on the Si(111) substrates, provides us correlation between magnetic properties and interface roughness. The average height, grain size and surface roughness of these Ag islands were tuned by varying the deposition thickness of Ag film (0~20 nm). Thicker Ag buffer layer enhanced the formation of films texture while increased the surface roughness as well. A magnetic anisotropy transition of Co films from biaxial into isotropic was observed by the longitudinal mode of magneto-optical Kerr effect with increasing Ag buffer thickness. The Ag buffer islands not only play an important role on the magnetoresistance transition but also provide a resultant domain-wall-pinning of Co films.

Key words: Ag(111) islands, Co films, roughness, magnetic anisotropy, and magnetoresistance

1. INTRODUCTION

The surface/interface roughness influences magnetic properties such as, magnetic anisotropy, coercivity, magnetic domain and magneto-transport properties of the magnetic materials [1-5]. From application point of view, the surface/interface effect is the more important one than others because of the magneto-devices tend to reduce its spatial size.

Various works on the relationship between surface roughness, coercivity and magnetoresistance of thin and ultrathin films, has been carried out [6-10]. Therefore, to understand the interrelationship between roughness and magnetic properties of epitaxial Co films, we varied different thicknesses of Ag films on Si(111) substrates to study the surface scattering induced magnetoresistance (MR) effect and magnetic properties. It is well known that anisotropic magnetoresistance (AMR) measurement was strongly affected by the direction of current relative to the magnetic field. If the current is parallel to the field, valley-shaped MR peaks are observed, while if the current is perpendicular to the field, bell-jar-shaped MR peaks are obtained [11]. The phenomena of gradually transition from positive magnetoresistance (PMR) when H//I to negative magnetoresistance (NMR) when H⊥I are typical AMR. The evolution of AMR in magnetic films is important in studying the various magneto-transport phenomena in magnetic materials and also necessary to the applications of large-size memory devices or the magnetic sensor. In this study, the transition of MR signal and the magnetic properties of single Co film strongly influenced by the Ag buffer islands will be discussed.

2. EXPERIMENT

Ag buffer islands of thickness t nm ($0 < t < 20$) were first deposited on chemical etched Si(111) substrates at 500°C by a Knudsen cell with deposition rate of around 0.05 Å/sec. And then Co (9 nm) films were deposited onto the different thicknesses Ag(111) islands. The deposition rate and temperature of the Co films were controlled at about 0.05 Å/s and 100°C, respectively. The background vacuum was down to 10^{-10} Torr, and the growth pressure was controlled below 2×10^{-8} Torr during deposition. The crystal structure was characterized by *in-situ* reflection high-energy electron diffraction (RHEED) and *ex-situ* θ-2θ□x-ray diffraction (XRD). The surface and cross-sectional morphologies of the Co films were imaged by atomic force microscopy (AFM) and transmission electron microscopy (TEM), respectively. The magnetic anisotropy was investigated by angular-dependent longitudinal magneto-optical Kerr effect (LMOKE). The magneto-resistive response curve, R(H), were measured by a four-point probe technique. The current I was fixed at 20 mA and the magnetic field H was applied in the film plane. The rotation angle, φ, is between the direction of the current and the orientation of the applied magnetic field.

3. RESULTS AND DISCUSSION

3.1 Structure identification

Figs. 1(a) and 1(b) show the typical RHEED patterns of Si(111) substrate and the Ag(111) buffer layer with the probing e-beam aligned along the Si[011] in–plane direction. Fig. 1(b) indicates that the Ag atoms grow epitaxially on the Si(111) with 4:3 atomic matching in

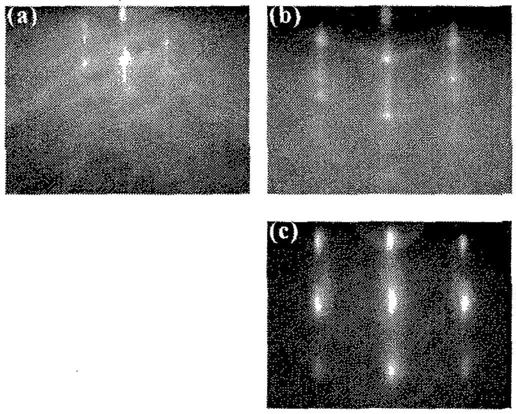

Fig. 1. RHEED patterns of Si/Ag/Co film with the probing e-beam aligned along the Si[011] direction. (a) Si(111) substrate, (b) 20nm thick buffer Ag, and (c) 9 nm thick Co layer.

two-dimensional superlattice [12]. Fig. 1(c) shows that the Co film onto the Ag layer followed the Ag buffer pattern growth. The argument will be proved by cross-sectional TEM image and surface morphology, as seen in Fig. 2 and Fig. 3. The investigations of XRD and RHEED patterns show that the main epitaxial relations are Si(111) // Ag(111) // Co(111), and Si[$\bar{1}$10] // Ag[$\bar{1}$10] // Co[$\bar{1}$10].

3.2 Morphology of Ag pyramidal islands

Due to the surface energy consideration [13, 14], the Ag film shows islands structure as observed by the cross-sectional TEM image seen in Fig. 2. From the Ag(110) poles viewed the sidewalls of these Ag islands are just {111} planes. This aspect of Ag islands growth is also supported by AFM images. Figure 3(a) show the surface morphology of the Si substrate after cleaning and 650°C heat treatment for 1 hour; and 3(b) with Ag thickness 20 nm grown on Si(111). Comparing with the TEM image, we can know that the morphologies of Co films are strongly followed the underlying Ag(111) islands with pyramidal-like grains as shown in Fig. 3(b). To show the change of surface morphology in the vertical direction, a line scan from each of the AFM image was plotted in Fig. 3(c) and 3(d) by keeping the same vertical scale. It can be understood that the vertical roughness and height increased with the Ag buffer thickness t. AFM line scans also show that the average height, grain size and surface roughness of these Ag islands were tuned by varying the thickness of Ag film as seen in Fig. 3(d). From AFM line scans, we obtained the roughness parameters versus underlying Ag thickness. The roughness parameters are the vertical interface width w, the lateral correlation length ξ, the roughness exponent α, these values could be calculated local surface slope ρ [15]. So Ag(111) islands system was provided as a good template to study the magnetic properties influenced by rough surfaces.

3.3 In-plane coercivity of Co films versus azimuthal angle distributions

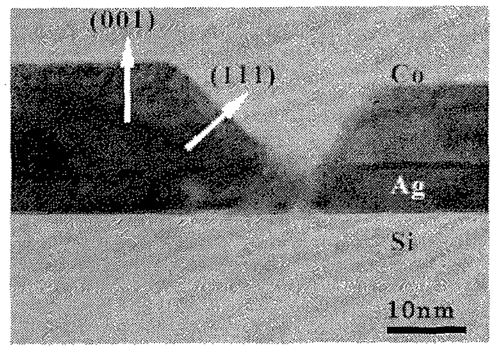

Fig. 2. Cross-sectional TEM micrograph of the Co film grown on Si(111) substrate with 20 nm thick Ag buffer layer.

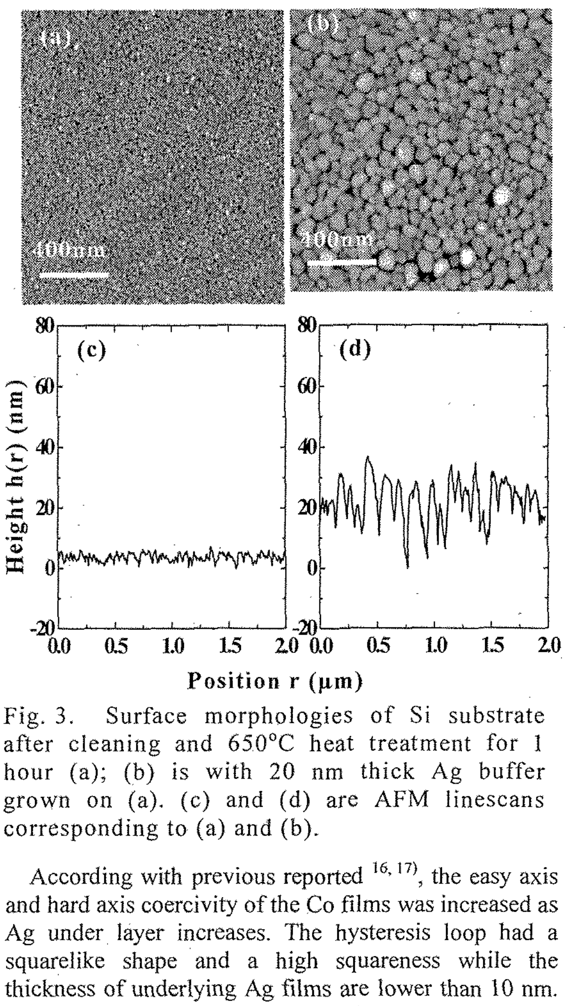

Fig. 3. Surface morphologies of Si substrate after cleaning and 650°C heat treatment for 1 hour (a); (b) is with 20 nm thick Ag buffer grown on (a). (c) and (d) are AFM linescans corresponding to (a) and (b).

According with previous reported [16, 17], the easy axis and hard axis coercivity of the Co films was increased as Ag under layer increases. The hysteresis loop had a squarelike shape and a high squareness while the thickness of underlying Ag films are lower than 10 nm. When Ag under layer thickness is over 20 nm, the coercivity value of hard axis is nearly close to easy axis. From rms roughness of Co films increases linearly with the Ag thickness, it reveals that the Ag rough surface acts as a pinning source.

In-plane magnetic anisotropy of Co films was investigated by the longitudinal magneto-optical Kerr effect (LMOKE). The biaxial magnetic anisotropy while with or without Ag under layer between Si and Co films as depicted in Fig 4(a), and (b), respectively. Note that

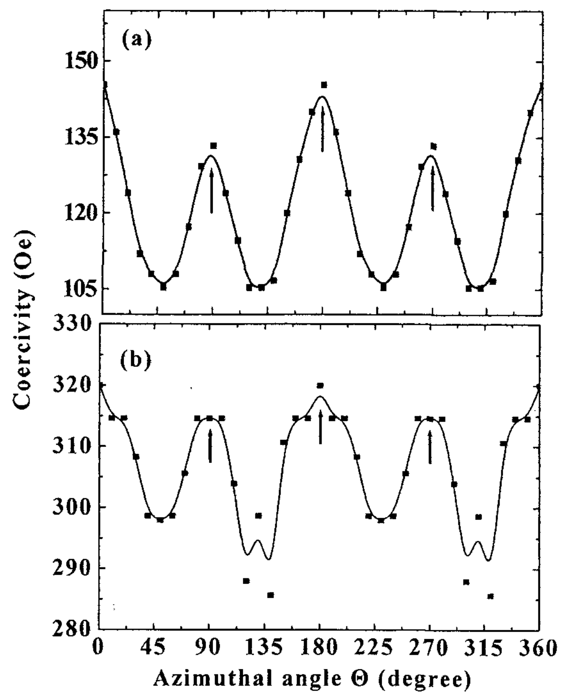

Fig. 4. Azimuthal distributions of the Co coercivity for (a) without Ag buffer, and (b) with 10 nm thick Ag buffer grown on the Si(111) substrates.

the arrows in Fig. 4 indicate the easy-axis directions of Co films. However, for Co films grown on the Ag(111) islands with thicknesses greater than 20 nm, the Ag surface roughness induced domain wall pinning contributing to the coercivity and showing magnetically isotropic behavior. At the same time, the disappearance of biaxial anisotropy could be due to the increase of the roughness induced in-plane demagnetization factor [18, 19]. In-plane demagnetization factor can be calculated by:

$$N = \pi w^2/\xi d, \qquad (1)$$

given by the roughness parameters, w: vertical width, ξ: lateral correlation length, and d: film thickness. However, in-plane demagnetization factor, N, increased with surface roughness dramatically, as obtained from Fig. 3 [19].

3.4 Magnetoresistance transition of Co films

The variation of magnetoresistance (MR) ratio can be observed by either the resistivity, ρ, or the resistivity change, $\Delta\rho$, of Co films under an in-plane magnetic field 1000 Oe at 25°C. Fig. 5 show the MR vs H curve of the Co films grown on (a) 5 nm and (b) 20 nm thick Ag buffer layer, respectively. The solid and dot lines represent the current are parallel and perpendicular to the field, respectively. When the thicknesses of Ag under layer are lower than 10 nm, the typical AMR behavior transition from positive magnetoresistance (PMR) when H // I to negative magnetoresistance (NMR) when H ⊥ I are clearly as seen in Fig. 5(a) [11, 20]. The current is parallel to the magnetic field, only the PMR contributes to the MR signal, and the valley-type

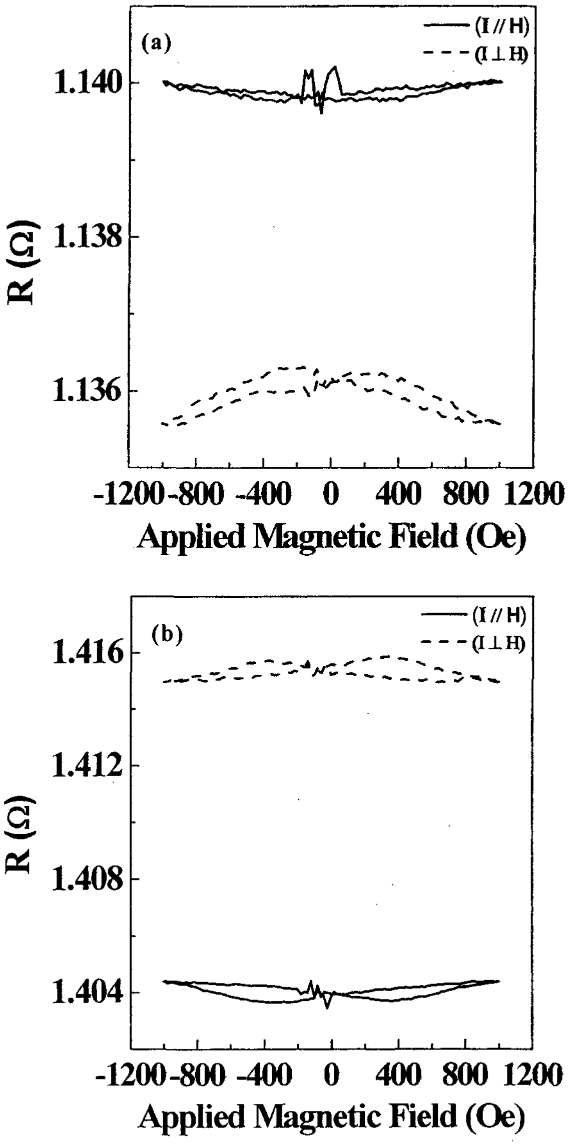

Fig. 5. MR loops of the Co films grown on (a) 5 nm, and (b) 20 nm thick Ag buffer layer. The solid and dot lines represent the current being parallel and perpendicular to the field, respectively.

MR peaks are observed. As the φ increased to the 90° (H ⊥ I), bell-jar shaped MR peaks are obtained by NMR contributed. And we also observed the gradual change of MR-H curves start from the PMR dominant range of φ when $\varphi \leq 40°$ to the NMR dominant curves when $\varphi \geq 50°$. At this range ($40° \leq \varphi \leq 50°$), both NMR and PMR contribute to the MR peaks at the same time. The negative MR will fully compensate the positive MR and will lead to a straight line. So the MR shape is strongly depended on the rotation angle φ, the angle between the direction of the current and the orientation of applied magnetic field.

The AMR curve depends on many factors, such as the film thickness, grain size, film surface conditions and shape anisotropy. The development of AMR in magnetic films is very important in studying the various magneto-transport phenomena in magnetic materials and also significant in technological applications. The peculiar MR-H curves in Fig. 5(b) showed that when Ag islands formed (thickness of Ag under layer $\geq$ 20 nm) as seen in Fig. 2, the (111) sidewalls started to contribute to the MR signal, the resistance value in the H⊥I mode is greater than that in H//I mode. In fact, the phenomenon is not typical AMR behavior. It indicates the {111} sidewall of Ag islands display an important role on the magnetoresistance transition of the Co films. The comparison in detail will be reported in the future.

4. CONCLUSIONS

We successfully used Ag(111) islands to do the template and easily controlled the interface roughness between Ag and Co films via the thickness variation of Ag buffer films. The in-plane magnetic anisotropy transition was found from biaxial into isotropic of the Co films when the thickness of Ag under layer greater than 20 nm. Ag islands were key factors on the magnetization reversal of the Co film that also contribute to the in-plane demagnetization factor.

Acknowledgments

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