Magnetic properties of Co/Ag/Co films
grown on Ag(100) nanometer-scale islands

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Self-assembled Ag(100) islands on Si(100) substrate were fabricated by using the molecular beam epitaxy
 technique. Co/Ag/Co films were then grown onto Ag films at 100 °C. We have experimentally demonstrat-
ed that the magnetic behavior of Co/Ag/Co films is strongly dependent on the thickness and morphol-
ogy of the Ag(100) islands that serve as a buffer layer. The buffer layer designed to reduce the surface
free energy forms isolated pyramidal islands with [1 1 1] sidewalls on the Si(100) substrate, and provides
feasibility to study the correlation between magnetic properties and interface roughness. Ag islands also
play an important role in the magnetoresistance transition of Co/Ag/Co films. The roughened Ag(100)
surface facilitates texture growth of Co/Ag/Co films and provides a resultant domain-wall-pinning, that in
turn contributes to the in-plane demagnetization factor.

1 Introduction Surface roughness influences the magnetic properties such as magnetic anisotropy,
coercivity, and magneto-transport properties of magnetic thin or ultrathin films [1–3]. Various works on
the relationship between surface roughness, coercivity and magnetoresistance of thin films and
multilayers have been carried out [4–7]. Very few works have been done on the shape effect of a buffer
on the magnetic properties of multilayers on top [8]. Therefore, it would be interesting to understand the
relationship between island-shaped buffer layer and magnetic properties of epitaxial Co/Ag/Co
multilayers. The anisotropic magneto-resistance (AMR) has been extensively studied [9–12], but not on
the multilayers of our scheme. So, in this article, the transition in MR curves and the magnetic properties
of Co/Ag/Co films under the influence of interface roughness between Co/Ag/Co films and Ag buffer
layer will be discussed.

2 Experiment Ag buffer layers of thickness \( t \) nm (0 < \( t \) < 40) were first deposited at 500 °C by a
Knudsen cell with deposition rate around 0.05 Å/s on Si(100) substrates after chemical etching and
650 °C outgasing for 1 h. Then Co(5 nm)/Ag(3 nm)/Co(4 nm) films were deposited onto the Ag(100)
islands at 100 °C with deposition rate of 0.05 Å/s. The background vacuum was down to 6 × 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 X-ray
diffraction (XRD). The surface morphology and cross-sectional micrograph were observed by atomic
force microscopy (AFM) and transmission electron microscopy (TEM), respectively. The magnetic
Fig. 1  RHEED and XRD patterns of Si/Ag/Co/Ag/Co films with the probing e-beam aligned along the Si[010] in-plane direction: RHEED patterns of (a) Si(100) substrate, (b) 5 nm thick Ag buffer; (c) and (d) are RHEED and XRD patterns for Co(5 nm)/Ag(3 nm)/Co(4 nm) films on (b), respectively.

anisotropy was investigated by the angle dependent longitudinal magneto-optical Kerr effect (LMOKE). The magnetoresistive response curves, $R(H)$, were measured by a four-point probe technique with the current $I$ fixed at 20 mA.

3 Results and discussion
3.1 Structure identification  Figures 1(a) and (b) show RHEED patterns of the Si(100) substrate and the Ag(100) buffer layer, respectively, with the probing e-beam aligned along the Si [010] in-plane direction. Figure 1(b) indicates that the Ag buffer grows epitaxially on Si(100) by 4 : 3 coincidental atom matching [13]. Figure 1(c) and (d) show the RHEED and XRD patterns of the Co/Ag/Co films on the 5 nm thick Ag buffer. The Co film grows following patterns of the Ag buffer layer. The argument is further proved by cross-sectional TEM images and surface morphology, as shown in Fig. 2. The investigations of XRD and RHEED patterns show that the main epitaxial relations are Si(100)//Ag(100)//Co(100), and Si[011]//Ag[011]//Co[011]. If the Ag buffer layer was not used, the crystal structure of Co/Ag/Co films was polycrystalline.

3.2 Morphologies of Co/Ag/Co films  Due to the constraints of surface energy [14], the buffer Ag film shows a self-assembled island structure as observed by the cross-sectional TEM micrograph shown in Fig. 2(a). The sidewalls of these Ag islands are {111} planes. This aspect of island growth is also supported by AFM micrograph as shown in Fig. 2(b). Comparing with the TEM micrograph, it is known that the morphologies of Co/Ag/Co films follow intimately the underlying Ag(100) islands and display pyramidal grains. From AFM line scans shown in Fig. 2(c), the roughness parameters versus underlying Ag thickness were obtained. The roughness parameters correlate to the vertical interface width $w$, the lateral correlation length $\xi$, and the roughness exponent $\alpha$. These values can be used to calculate the local surface slope $\rho$ [15]. Equation (1) shows the in-plane demagnetization factor represented by

$$N = \pi w^2 / \xi d,$$

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Fig. 2  Cross-sectional TEM micrograph of the Co/Ag/Co films grown on Si(100) substrate with 40 nm thick Ag buffer (a); (b) is AFM morphology of (a), and (c) is a line scan of roughness corresponding to (b).
$d$ is the film thickness. In-plane demagnetization factor, $N$ [16], increases with surface roughness dramatically. AFM line scans also show that the average height, grain size and surface roughness of these Ag islands change by varying its thickness.

### 3.3 In-plane magnetic anisotropy

It is understandable that the coercivity of Co/Ag/Co films increased with increasing roughness of the Ag buffer [17]. The hysteresis loops possess a square-like shape and a high squareness while the thickness of the Ag buffer is lower than 20 nm. The in-plane magnetic anisotropy of Co/Ag/Co films was investigated by the longitudinal magneto-optical Kerr effect (LMOKE). The uniaxial magnetic anisotropy without or with a 20 nm thick Ag buffer layer between Si and Co/Ag/Co films is depicted in Fig. 3(a) and (b), respectively. When the thickness of the Ag buffer is above 20 nm, Co/Ag/Co films become magnetically isotropic. Note that the arrows in Fig. 3 indicate the easy-axis directions of Co/Ag/Co films. However, for the Co/Ag/Co films grown on the Ag(100) islands that have a thickness greater than 20 nm, the Ag surface roughness induced domain-wall-pinning starts to contribute to the coercivity and shows magnetically isotropic behaviour. At the same time, the disappearance of uniaxial anisotropy could arise from the increase of the in-plane demagnetization factor induced by the roughness.

![Fig. 3](image_url) Azimuthal distributions of the Co/Ag/Co coercivity for (a) without Ag buffer, and (b) with 20 nm thick Ag buffer grown on the Si(100) substrate.

![Fig. 4](image_url) MR loops of the Co/Ag/Co films grown on (a) 10 nm and (b) 20 nm thick Ag buffer layer. In (a), the solid circle and square symbols represent the current being parallel and perpendicular to the field, respectively. In (b), the solid and dot lines represent the current being parallel and perpendicular to the field, respectively.
3.4 Magnetoresistance transition  Figure 4(a) shows the MR vs. $H$ curves of the Co/Ag/Co films with 10 nm thick Ag buffer. The solid circle and square symbols represent the current being parallel and perpendicular to the field, respectively. The solid symbols represent the electrical resistance with $H$ scanning from the positive direction to the negative, and the hollow ones, the reverse direction. The curve in the $H \parallel I$ mode is very special, indicating a superposition combined with a NMR curve and a PMR curve. The resistance value in the $H \parallel I$ mode is greater than that in the $H \perp I$ mode as seen in Fig. 4(a). The phenomenon is consistent with the typical AMR. It is a positive magneto-resistance contributed to the MR signal when $H \parallel I$ and a negative magneto-resistance when $H \perp I$ typical of AMR behaviour. The special curve is due to the Ag buffer layer effect that contributes to the magneto-resistance signal. After the formation of Ag islands ($t \geq 20$ nm) as seen in Fig. 4(b), the sidewalls start to contribute to the MR signal and the resistance value in the $H \perp I$ mode is greater than that in $H \parallel I$ mode. The phenomenon is not typical of AMR. This indicates that the $\{111\}$ sidewalls of Ag islands play an important role on the magneto-resistance transition of the Co/Ag/Co films. The $R(H)$ loops, measured under an applied field 1000 Oe, have a sharp degraded point that we defined as $H_x$, as shown in Fig. 4(b). The $H_x$ of the Co/Ag/Co films also increases linearly with the roughness of the underlying Ag buffer. Compared with the change in coercive force, it appears that the roughened Ag surface induces domain-wall-pinning that also contributes to the in-plane demagnetization factor.

4 Conclusions  We have successfully manipulated self-assembled Ag(100) islands with $\{111\}$ sidewalls grown on Si(100) substrates as a template to further deposit Co/Ag/Co multi-layers. The interface roughness between underlying Ag buffer and later grown Co/Ag/Co films can be controlled via the thickness control of the Ag buffer. The disappearance of magnetic anisotropy is possibly associated with the increase of the in-plane demagnetization factor induced by the roughness. The Ag islands were the key factor for the magneto-resistance transition of the Co/Ag/Co films.

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References