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Comparative Study in Magnetic Properties of Co Ultrathin Films on Flat and Sputtered Pt(111) Surfaces

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The *in situ* magneto-optic Kerr effect was used to study the magnetic properties of Co ultrathin films grown on a flat and a sputtered Pt(111) surface. The perpendicular magnetic anisotropy appears for Co on the flat Pt(111) surface with a thickness of less than 4.0 ML and it changes to in-plane after the coverage of Co is more than 6.5 ML, whereas both the out-of-plane and in-plane anisotropy occur on the sputtered Pt(111) surface. The coercive force decreases as the Co coverage increases for the flat Pt(111) surface, but it is independent of the thickness for the sputtered one. A surface in island growth and surface roughness seem beneficial to the reversal of a magnetic domain wall. Thermal energy also helps the domain wall motion. The perpendicular Kerr intensity increases in a linear relation with thickness of Co before the magnetization turns to in-plane for the flat surface, and it is a smooth curve with a maximum at 5.5 atomic monolayers of Co for the sputtered surface. The Curie temperature of Co thin films on the flat Pt(111) was measured. The Curie temperature increases as the thickness of Co increases. An enhancement of perpendicular magnetic anisotropy was observed when a Co-Pt alloy is developed. The hybridization of electronic states in the formation of a Co-Pt surface alloy and the large spin-orbit coupling in this system are possible mechanisms for the enhancement.

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I. Introduction

The study of magnetic thin films is of current scientific and technological interest. Co-Pt systems have attracted considerable interest as a candidate of the magneto-optic recording media because these systems have a high perpendicular magnetic anisotropy, high coercivity and large magneto-optic Kerr signal [1-3]. A number of experimental investigations have been performed on the Co/Pt multilayers, thin film, and alloy [4-9]. Well et al. reported an overall 50% enhancement in the polar Kerr signal for 250 nm thick alloying film of $Co_{.28}Pt_{.72}$/quartz compared to the Co/Pt multilayers [4]. The transformation from fcc to hcp of the Co stacking results in about a 25% enhancement of magnetization at the Co/Pt(111) interface studied by Ferr *et al.* in surface x-ray diffraction [5]. Train *et al.* confirmed that the magnetic anisotropy and coercivity of $Pt/Co/Pt/Al_2O_3$ are strongly influencd by the growth temperature [10]. In this paper, we report a giant enhancement in the Kerr signal of Co ultrathin films deposited on Pt(111) after Co-Pt

alloying. The magnetic properties of Co/flat Pt(111) and Co/sputtered Pt(111) were comparatively studied by the surface magneto-optic Kerr effect (SMOKE) technique. The change in coercivity and magnetic saturation as a function of the thickness, and a function of temperature of the Co thin films are discussed. The Curie temperature relative to the film thickness of Co was also investigated. The mechanism of the enhancement of the Kerr signal is discussed.

II. Experiment

Experiments were conducted in an ultrahigh vacuum (UHV) chamber with a base pressure in the range of 10^{-10} Torr. The UHV chamber was equipped with instruments for low energy electron diffraction (LEED), Auger electron spectroscopy (AES), and SMOKE measurements. The Pt(111) surface was cleaned by means of Ar ion bombardment and subsequent annealing cycles. The kinetic energy of the Ar ions employed for the etching was 1.7 keV. The annealing temperature was 1050 K. The sputtering-annealing cycles were continued until a well-ordered $p(1 \times 1)$ LEED pattern with bright, sharp spots and a low background was observed. To remove the residual carbon, the sample was heated to 870 K in an oxygen pressure of 5×10^{-7} Torr before sputtering. The chemical impurity on the surface was checked by means of AES. A cobalt wire coil with purity of 99.997% was used to evaporate Co atoms. The pressure during Co deposition was kept near about 2×10^{-9} Torr at an evaporation rate of about 0.1 ML/min. The thickness of the Co overlayer was determined by Auger signals versus time plots, LEED intensity oscillation and a quartz balance thickness monitor, which have been described in detail elsewhere [11].

A p-polarized He-Ne laser with a wavelength of 632.8 nm was used as the light source for the SMOKE measurement. The SMOKE arrangement was thus able to measure the magneto-optic Kerr-response by monitoring the change of the reflective intensity, which is proportional to the Kerr rotation. Thus the Kerr signal is proportional to the magnetization of a magnetic material [12]. Because of its monolayer sensitivity, the SMOKE is suitable for measuring the hysteresis loop for a magnetic ultrathin film. The polar and longitudinal Kerr signal were obtained by rotating an electromagnet in the UHV chamber with the maximal magnetic field of 950 Oe.

III. Results and discussion

Co ultrathin films were deposited on the Pt(111) surface at 325 K. The Kerr signals versus the magnetic field of different coverages of the Co films on the flat Pt(111) surface are shown in Fig. 1. All SMOKE measurements were performed at 325 K. The hysteresis loops appear only in the polar configuration when the coverage of the Co film is less than 4.0 ML. The easy axis of the magnetization is the out-of-plane direction. As the film thickness increases to 4.4 ML, both longitudinal and polar hysteresis loops appear. As the film thickness increases to over 5.8 ML only the longitudinal hysteresis loop was observed and the easy axis of the magnetization changes to the in-plane direction. These results are consistent with that of the study by magnetic circular x-ray dichroism [13]. From our LEED and AES observations, the growth of the Co overlayer tends to be layer-by-layer at the initial stage of the growth [11]. In such a film, the magnetocrystalline anisotropy is strong. This anisotropy causes the out-of-plane easy axis of magnetization. As the Co thickness increases, the growth of the Co overlayers tends to be three-dimensional island growth and the surface anisotropy is no longer dominant [11]. Therefore, the polar Kerr intensity vanishes and the longitudinal one persists.

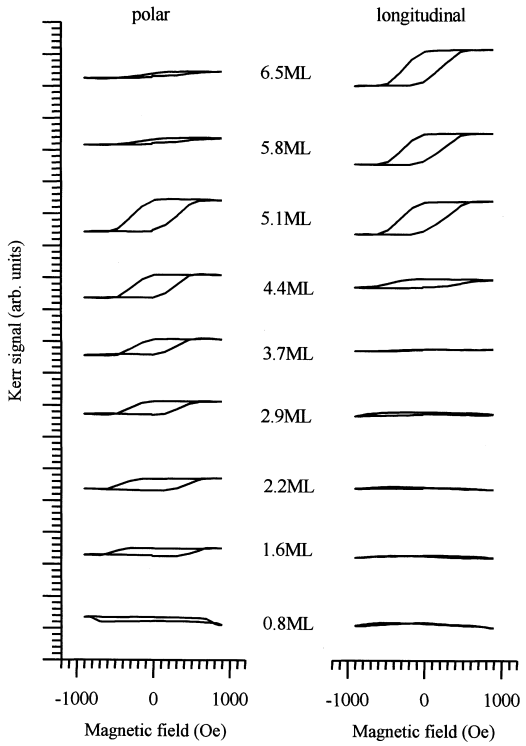

FIG. 1. The Kerr signals in polar and longitudinal configurations versus magnetic field for different thicknesses of Co on the flat Pt(111) surface. The perpendicular magnetic anisotropy occurs between 0.8 and 3.7 ML.

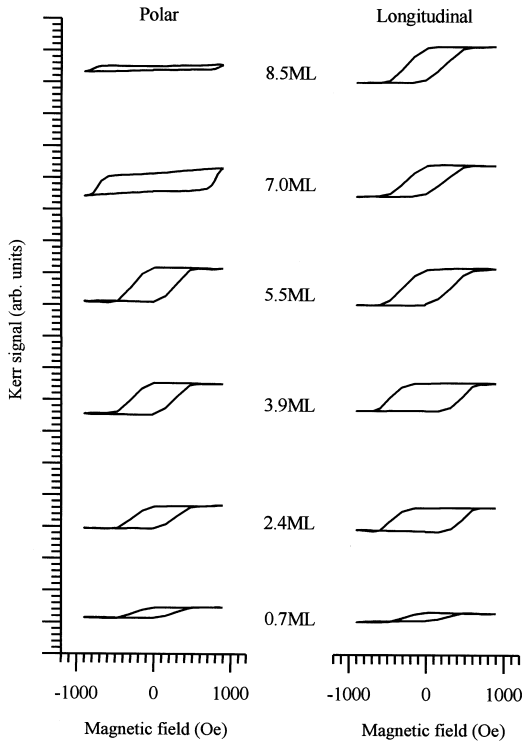

FIG. 2. The Kerr signals in polar and longitudinal configurations versus magnetic field for different thicknesses of Co on the sputtered Pt(111) surface. Both longitudinal and polar Kerr signals occur for Co thickness between 0.7 and 7 ML.

The hysteresis loops of Co/sputtered Pt(111) are shown in Fig. 2. Argon ions with a kinetic energy of 1.7 keV were used to sputter a well-ordered Pt(111) surface for 5 minutes. The Pt(111) surface is rough and has a lot of steps when the surface is sputtered at a temperature below 550 K [14]. LEED spots became dimmer after Co atoms were deposited on the sputtered Pt(111) surface. The Co film shows three-dimensional island growth. The Kerr signals occur in both the longitudinal and the polar configurations when the Co thickness is between 0.7 and 7.0 ML. The polar configuration disappears after the coverage of Co is higher than 8.5 ML. The disappearance of perpendicular uniaxial magnetic anisotropy of Co/sputtered Pt(111) is attributed to the fact that the magnetocrystalline anisotropy has diminished. In addition, the sputtered Pt(111) surface becomes rough and may result in complicated orientations for the Co islands [15].

The thickness dependence of the coercive force, H_c, is interesting. Since the perpendicular magnetic anisotropy is the most important property in this system, we only study the Co thickness, t, dependence of H_c in the perpendicular magnetic anisotropy. The relation between H_c and t for Co films on the flat Pt(111) surface is shown as the solid line in Fig. 3(a). H_c decreases as the

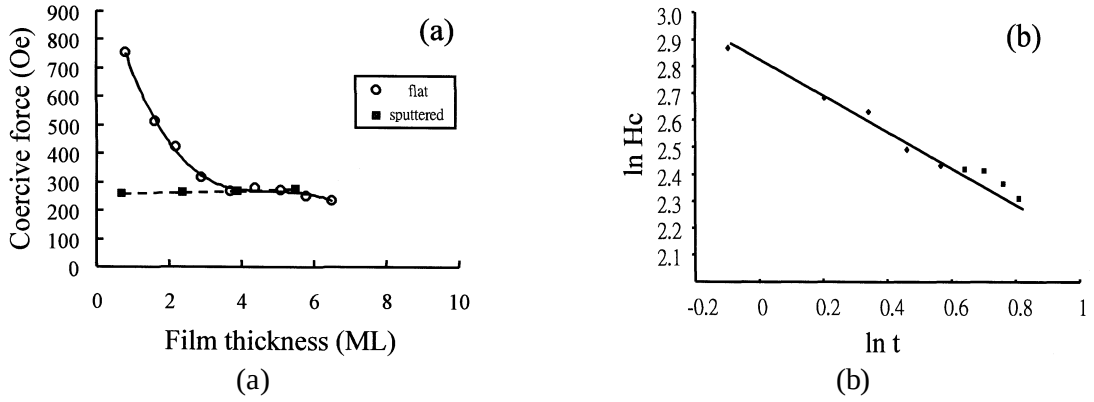

FIG. 3. (a) The coercive force in the polar configurations as a function of Co film thickness for Co/flat Pt(111) (solid line) and for Co/sputtered Pt(111) (dash line). H_c decreases as t increases for Co/flat Pt(111), but H_c is independent of t for Co/sputtered Pt(111). (b) Logarithm of H_c versus logarithm of t, the relation is linear for Co/flat Pt(111). The slope of the straight line is $¡ 0:66 ¼ ¡ 2=3$, i.e., H_c / $t^{¡ 2=3}$.

thickness of Co film in increases for the flat surface. The decrease follows the $t^{¡ 2=3}$ power law as shown in Fig. 3(b). H_c decrease with a film thickness was observed in both the Au/Co/Au system [16], and (Co 3.8 nm/Gd 3.0 nm) £ 10 multilayers [17]. Usually a coercive force is related to both the nucleation process and the pinning of domain walls. An H_c decrease as t increases is the characteristic of the Bloch domain-wall motion, and an H_c increase as t increases is the characteristic of the Neel domain-wall motion if the spin reversal is mainly governed by domain-wall movement rather than random nucleation processes [18, 19]. For example, Fe/Si(111) [19] and (Co 3.0 nm/Gd 3.0 nm) £ 20 multilayers [17] are in the latter case. Our system seems to belong to the case of Bloch domain wall movement.

The thickness dependence of the coercive force in perpendicular magnetic anisotropy for Co films on the sputtered Pt(111) surface is shown as the dashed line in Fig. 3(a). H_c almost keeps a constant value of 250 Oe for the coverage lower than 5.5 ML. Beyond 5.5 ML, the perpendicular magnetic anisotropy tends to disappear. We can conclude that H_c is independent of the thickness of the Co in the ultrathin range within the experimental error. Comparing both of the curves in Fig. 3(a), $H_c ¼ 250$ Oe for 0.7-5.5 ML Co/sputtered Pt(111) and this value is close to that of 6.5 ML Co/flat Pt(111). We can speculate that the growth of Co on the flat Pt(111) surface changes from the layer-by-layer growth to the 3-D island growth at approximately 6.5 ML, and the growth of Co thin films on the sputtered Pt(111) surface is an island growth. These results indicate that the reversal of the spin orientation in the out-of-plane direction can be achieved by using a smaller magnetic field for the magnetic thin film grown in islands. A rough magnetic thin film seems to help the reversal of a magnetic domain in the Co/Pt(111) system.

For further investigation of the temperature effect on the coercive force, we measured H_c as a function of temperature. Hysteresis loops were taken after the thin film was in thermal equilibrium and persisted for 3 minutes at each temperature. The result of 1.0 ML Co/flat Pt(111) is shown in Fig. 4. H_c decreases when the temperature, T, increases. This result agrees with that

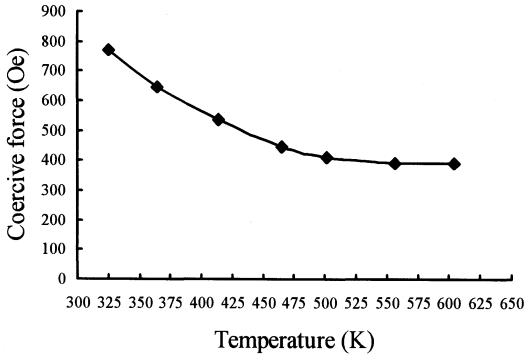

FIG. 4. Temperature dependence of the coercive force in polar configuration for 1.0 ML Co/flat Pt(111), see the text.

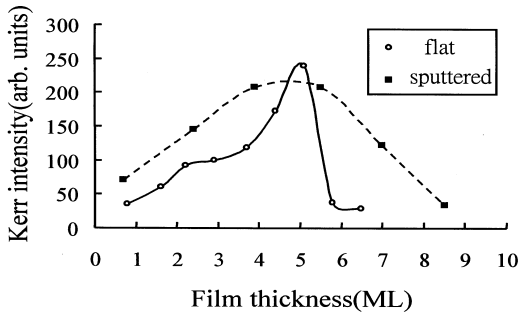

FIG. 5. Thickness dependence of the saturated polar Kerr intensity for Co/flat Pt(111) (solid line) and for Co/sputtered Pt(111) (dash line).

of 50-nm-thick Co-Pt alloy studied by Shiomi *et al*. [20]. The same behavior of H_c versus T was observed in the NiO/Co/NiO/Py/NiO system [21]. The relation between the coercive force and the temperature of a thin film can be described by the mathematical formula: $H_c = H_{c0}(1 - \sqrt{\frac{T}{T_B}})$, where H_{c0} is the coercive force at $T = 0$ K, and T_B is the blocking temperature [20]. Our system is qualitatively consistent with the prediction of this formula. $H_{c0} = 1974$ Oe and $T_B = 816$ K were found in our after fitting. This result means that the ferromagnetic characteristics changes to a paramagnetic characteristics after $T > T_B$ if we assume that the system is a composite of finite size of Co particles [22]. The result in Fig. 4 also indicates that a high temperature helps the reversal of perpendicular magnetization, because thermal energy enhances the domain-wall movement.

The saturated polar Kerr intensity, which is proportional to the saturated perpendicular magnetization, M_s, as a function of the thickness of Co for the flat surface is shown as the solid line in Fig. 5. M_s is nearly in a linear relation with t less than 5 ML. Above 5 ML , the perpendicular magnetization decreases abruptly and the in-plane magnetization grows. The linear relation agrees with the measurement of an epitaxial Co ultrathin film grown on Pd(111) [23]. The M_s as a function of t for the sputtered surface is shown as the dashed line in Fig. 5. M_s increases with t for the thickness less than 5.5 ML and then it decreases monotonically. This result indicates that the maximum perpendicular magnetization for Co grown on the sputtered Pt(111) occurs at 5.5 ML, and finally the easy axis shifts to the plane of the thin film.

The temperature dependence of the hysteresis loops in the polar configuration for 2.0 ML Co on the flat Pt(111) surface is shown in Fig. 6 The Kerr intensities were measured after the sample temperature was at equilibrium and persisted for 3 minutes at each temperature. The Kerr intensity occurs only in the polar configuration when 2.0 ML Co grows on the flat Pt(111) surface as shown in Fig. 1. The Kerr signal decreases as T increases and it disappears at 675 K. This indicates that the Curie temperature, T_c, is around 675 K for 2.0 ML in this system. We further depict the relative magnetization, $M_s(T)/M_s(325\ K)$, versus T in Fig. 7 for the coverage $t = 1.0$, 2.0 and 6.0 ML. From Fig. 7, one can obtain the Curie temperatures of these thin films: $T_c = 625$

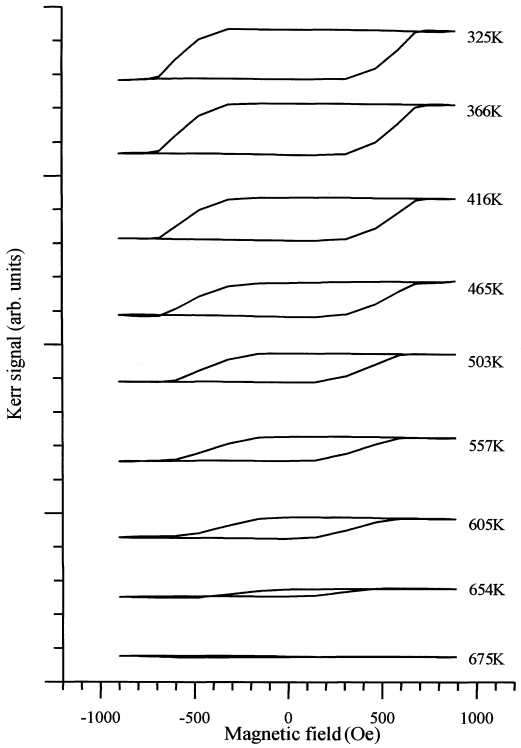

FIG. 6. The polar Kerr hysteresis loops at different temperatures for 2.0 ML Co/flat Pt(111). The Kerr signal is too small to be measured after $T > 675$ K.

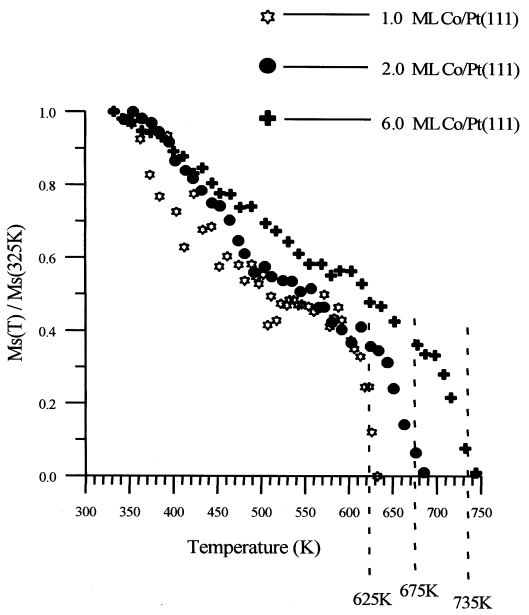

FIG. 7. The relative saturated perpendicular magnetization versus temperature for different coverages of Co. The Curie temperatures are 625 K, 675 K and 735 K for 1.0 ML, 2.0 ML and 6.0 ML respectively.

K, 675 K and 735 K for 1.0 ML, 2.0 ML and 6.0 ML, respectively. The fact that T_c increases with the thickness of a magnetic thin film and finally approaches to the bulk Curie temperature is well known [24, 25]. Our result follows this law.

After carefully examining the curves in Fig. 7, we discover that plateaus on the curves occur between 500 K and 575 K for 1.0 ML, and between 510 K and 590 K for 2.0 ML. The plateau region becomes smaller and no longer significant for 6.0 ML. From mean field theory, saturated magnetization versus the sample temperature is a smooth function. It decreases monotonically when the temperature increases. The observation of the unusual plateau of the curve for the relative magnetization versus the sample temperature may imply a counterpart of enhancement of the M_S. Fig. 8 shows Kerr hysteresis loops taken at 325 K in polar and longitudinal SMOKE for 2.0 ML Co/flat Pt(111) annealed at different temperatures for 3 min. It reveals only the perpendicular anisotropy as shown in Fig. 8(a). The polar Kerr intensity taken at 325 K increases drastically by about 250% after annealing at 710 K as shown in Fig. 8(b). The change of the coercive force is small, but the shape of the loop becomes perfectly square. Moreover, the polar Kerr intensity increases reaching a value of about 320%, and the longitudinal Kerr hysteresis loop

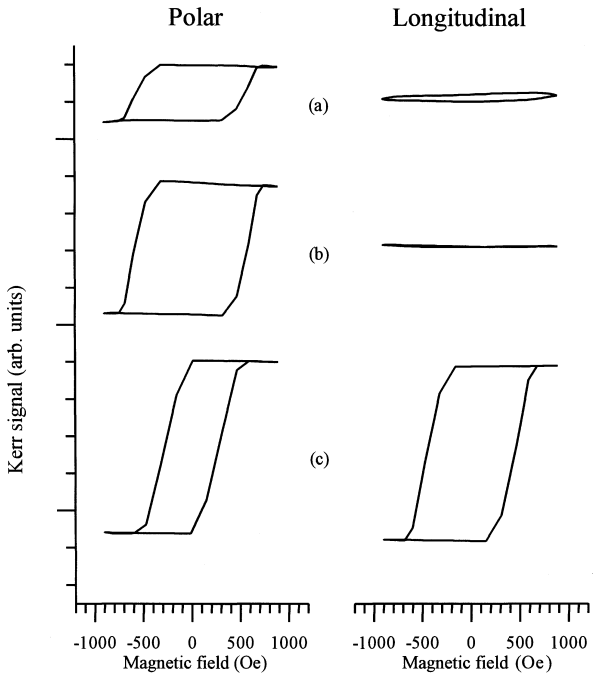

FIG. 8. The Kerr hysteresis taken at 325 K in the polar and longitudinal configurations for the 2.0 ML Co/flat Pt(111) annealed at different temperatures.

appears after annealing at 850 K as shown in Fig. 8(c). The coercive force, H_c, of the polar Kerr hysteresis loop decreases to about one half of the original value for annealing at 850 K.

The amount of the enhancement in Kerr intensity described above includes the difference in reflectivity between Co and the Co-Pt alloy. The reflectivity of Co and Pt are 0.66 and 0.75, respectively, when a photon energy of 2.0 eV (wavelength of 632.8 nm) is used [4, 26]. The reflectivity of Co-Pt alloy must be between these values. The amount of enhancement of M_s must be corrected by the reflectivity and the resulting enhancement is still a significant amount. The mechanism of the enhancement of the Kerr signal after annealing at high temperature is interesting. An AES study showed that Co atoms start to diffuse into the Pt(111) at 500 K and the formation of the Co-Pt alloy actively occurs between 700 K and 800 K for 2.0 ML Co/Pt(111) [27]. Therefore this enhancement is related to the formation of the Co-Pt alloy. The hybridization of the electronic states in the formation of the Co-Pt surface alloy, and the exceptionally large spin-orbit coupling of Co atoms in the Co-Pt alloy state may be the mechanism of this enhancement [4, 5]. Gallego *et al.* showed that the hybridization of the Pt and Mn electronic states causes the Mn atomic magnetic moment to increase to 3.17 $^{1}{}_{B}$ [28]. A recent theoretical study of the Co-Pt multilayer system has shown that the strong spin-orbit coupling causes a significant enhanced Kerr rotation [29].

It is interesting to see why the in-plane magnetic moment of the 2.0 ML Co/flat Pt(111) appears after annealing at 850 K. The uniaxial surface anisotropy and interface anisotropy are responsible for the perpendicular magnetization [30]. Most Co atoms diffuse into the bulk of the

Pt, but there were a few Co atoms staying on the upmost surface and a poor interface between the Co and Pt is formed after annealing at 850 K. We believe that the poor interface causes the raise of the in-plane magnetization. Both the perpendicular and the in-plane magnetization disappear after annealing at a higher temperature, because almost all the Co atoms diffuse into the bulk of the Pt. The enhancement was also observed in both the perpendicular and the in-plane magnetization after annealing for the 2.0 ML Co/sputtered Pt(111) surface. The amount of the enhancement is comparable to that of the flat Pt(111).

IV. Conclusion

The growth of Co ultrathin films on flat and sputtered Pt(111) surfaces was studied by LEED and AES. The magnetic anisotropy was comparatively studied by SMOKE for Co deposited on a flat Pt(111) and on a sputtered Pt(111) surface. The coercive force and Kerr intensity as a function of the thickness of the Co showed different behaviors for the flat and the sputtered Pt(111) surfaces. The curie temperatures of Co/flat Pt(111) are 625 K, 675 K, and 735 K when Co coverages are 1.0 ML, 2.0 ML, are 6.0 ML respectively. A giant enhancement in Kerr intensity after high temperature annealing was discovered. The mechanism of the enhancement of M_s was discussed.

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