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Enhanced magneto-optical effect due to interface alloy formation in Co–Pt (1 1 1) ultrathin films upon thermal annealing

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Abstract

After postdeposition annealing in the temperature range of 500–800 K, a highly enhanced magneto-optical Kerr response up to a maximal value 300% of that before annealing, is observed for 1–2 ML ultrathin Co–Pt (1 1 1) films. With help of low energy electron diffraction and Auger electron spectroscopy, this enhancement of magneto-optical response is found to be correlated to the Co–Pt alloy formation at interface. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Interface alloy; Magneto-optical Kerr effect; Perpendicular magnetic anisotropy; Ultrathin film; Thermal annealing

1. Introduction

Co–Pt based systems, such as multilayers and alloy thin films, have attracted intensive interest due to their application in data storage technology as promising magneto-optical media [1–3]. Numerous reports on this system indicate a complicated interplay between the magnetic or magneto-optical behavior and the Co–Pt alloy composition as well as the crystalline structure, which are sensitively affected by the growth temperature and annealing temperature [3–6]. The physical origin and a complete understanding of many findings in these studies often require a detailed characterization of crystalline structure and chemical composition at the interface of multilayers or thin films. As compared to multilayers, ultrathin films provides an ideal system for a controllable Co–Pt interface. This is because, in application of many surface sensitive analytical techniques, the structural and composition evolution at interface can be definitely extracted, and the related effects on magnetism can be thus more clearly identified. In this work, we will focus on evolution of magnetic and magneto-optical properties of the Co–Pt (1 1 1) films in an ultrathin limit upon postdeposition annealing. The annealing temperature is a sensitive parameter for the interdiffusion process at interface. Thermal annealing of the Co–Pt (1 1 1) films at appropriate temperatures can induce a metastable state of Co–Pt alloy at interface, which gives rise to a large enhancement of magneto-optical effect.

2. Experiment

The experiments were carried out in an ultrahigh vacuum (UHV) chamber with base pressure in the range 5×10^{-10} mbar. The UHV chamber was

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equipped with in situ facilities for low energy electron diffraction (LEED), Auger electron spectroscopy (AES), magneto-optical Kerr effect (MOKE), and thin film growth. A cobalt wire coil with purity of 99.997% was used to evaporate Co films. The pressure during the film growth was kept about 1×10^{-9} mbar at an evaporation rate of about 0.1 ML /min. The Co films were grown at 325 K and annealed afterwards at different temperatures up to 850 K. The structural ordering and chemical composition of the sample were checked by LEED and AES, respectively. The magnetic and magneto-optical properties were monitored by the MOKE measurement, using a p-polarized He–Ne laser (632.8 nm) as the light source. The linear polarizer was put in front of the light detector for detecting the reflective signal in the s-wave direction only. The obtained reflective intensity change in such an arrangement is proportional to the Kerr rotation in the magneto-optical Kerr effect. The polar and longitudinal Kerr measurements were performed by simply rotating an electromagnet in the UHV chamber with a maximal magnetic of 950 Oe.

3. Results and discussion

According to our MOKE results, the Co–Pt (1 1 1) films grown at 325 K reveal a perpendicular anisotropy at coverages up to 5 ML, supplying a consistent and comparable system with the previous study [7]. Fig. 1 reveals the polar remanence Kerr signal as a function of the sample temperature for the 2.2 ML Co–Pt (1 1 1). The Co film, as grown, is first heated from 325 to 790 K. As indicated by the solid squares in Fig. 1, the polar remanence signal in the first heating procedure remains almost unchanged for the sample temperature up to 620 K. Above 620 K, the remanence Kerr signal, surprisingly, increases with the temperature and reaches a maximal value around 700 K. For the temperature higher than 700 K, the remanence Kerr signal drops quickly to zero at 790 K. The finding of an increase in remanence signal with temperature deviates significantly from the behavior in usual ferromagnetic materials. After the first heating cycle, the sample is immediately cooled down to the room temperature. The corresponding remanence Kerr signal (empty squares in Fig. 1) is found to be not reversible with temperature, but increases with decreasing temperature and reaches at 325 K, a value about 250% of that before heating. It is also clear that, between 640 and 790 K, the remanence signal for the first cooling cycle is smaller than that for the first heating cycle. The sample is heated again to 790 K and then cooled down to the same temperature. Interestingly, the remanence Kerr signal is now reversible with temperature. The Kerr signals after the first heating cycle change reversibly with temperature. This finding indicates that, after the first heating up to 790 K, the 2.2 ML Co–Pt (1 1 1) should, from the magnetic point of view, become another "magnetic system" with different intrinsic temperature dependence.

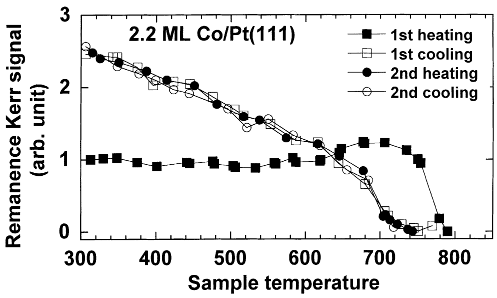

Fig. 1. Polar remanence Kerr signals as a function of the sample temperature for the 2.2 ML Co–Pt (1 1 1) for the first heating (solid squares), first cooling (empty squares), second heating (solid circles) and second cooling (empty circles) cycles.

In order to further investigate the effect of the annealing temperature on the perpendicular anisotropy and magneto-optical effect, we anneal the 2.2 ML Co–Pt (1 1 1) at different temperatures for 3 min. Fig. 2 compiles Kerr hysteresis loops measured at 325 K in the polar and longitudinal Kerr effect for the 2.2 ML Co–Pt (1 1 1) film annealed at different temperatures. The 2.2 ML film before annealing, as mentioned above, reveals a perpendicular anisotropy. After annealing at 710 K, the perpendicular Kerr response at 325 K increases drastically about 250% as compared to the value before annealing. The 2.2 ML films before annealing and after 710 K annealing still clearly reveal perpendicular anisotropy only. Annealing the film up to 850 K, the perpendicular remanence Kerr signal increases further to an amazing value about 320% of that before annealing. Nevertheless, the coercivity for the polar

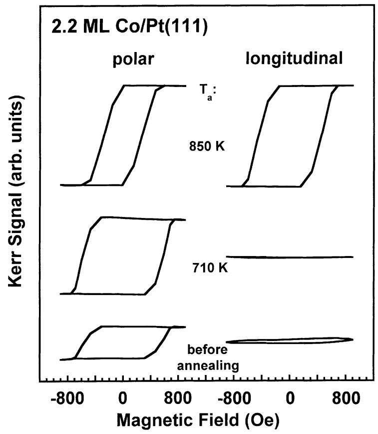

Fig. 2. Kerr hysteresis loops in the polar and longitudinal geometry for the 2.2 ML Co–Pt (1 1 1) film annealed at different temperatures T_a for 3 min. The Kerr signals were taken at 325 K.

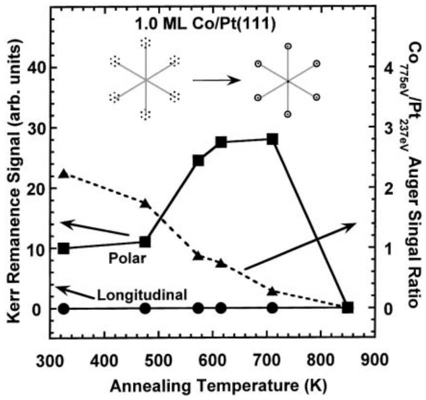

Fig. 3. Remanence Kerr signal in the polar (squares) and longitudinal (circles) geometry, the $Co_{775\ eV}/Pt_{237\ eV}$ Auger signal ratio (triangles) and the schematic LEED patterns for the 1.0 ML Co–Pt (1 1 1) annealed at different temperatures for 5 min. The measurement temperature is 325 K.

hysteresis loop become smaller and in the meantime, a significant in-plane signal is observed. This finding not only concerns the change in magneto-optical effects in polar or longitudinal geometry, but also clearly indicates a decrease of the perpendicular anisotropy and a raise of in-plane anisotropy or in-plane magnetic domain structure. This evolution of the perpendicular and in-plane anisotropy upon annealing at 850 K for the 2.2 ML film may be understood if we take both processes into account, a complete diffusion of the Co into the Pt substrate and the decrease of perpendicular anisotropy due to the poor interface quality upon thermal annealing at an extremely high annealing temperature. Before most of Co atoms diffuse deeply into the substrate, the perpendicular Kerr signal, which is attributed to the interface anisotropy, decreases significantly due to the poor interface quality upon thermal annealing at 850 K. Thus, before the Co atoms diffuses completely into the substrate and the ferromagnetic ordering of the total system vanishes, the in-plane Kerr signal or the in-plane magnetization appears.

For a deep insight into the origin of the enhancement of magneto-optical response, a more complete experiment including the MOKE, AES and LEED are performed for 1.0 ML Co–Pt (1 1 1). Fig. 3 combines the results of the remanence Kerr signal in both polar (squares) and longitudinal (circles) geometry, the $Co_{775\ eV}/Pt_{237\ eV}$ Auger signal ratio (triangles) and the schematic LEED pattern for the 1.0 ML films annealed at different temperatures for 5 min. All of the measurement temperatures are 325 K. The longitudinal remanence Kerr signal vanishes for all annealing temperatures, indicating the absence of an in-plane ferromagnetic ordering. The polar remanence Kerr signal starts to increase drastically at the annealing temperature above 500 K. At about 700 K annealing temperature, it reaches a maximal value about 300% of that before annealing. On the other hand, the Co–Pt auger signal drops rapidly in the same annealing temperature range with the large enhancement of Kerr signal, indicating a strong Co–Pt interdiffusion at interface. Above the 700 K annealing temperature, the polar remanence Kerr signal drops to zero at 850 K annealing temperature. The fact that the Co–Pt Auger signal ratio goes down to zero for the 850 K annealing temperature indicates, as mentioned above for the 2.2 ML film, a complete diffusion of the magnetic Co into the Pt substrate. This explains why the ferromagnetic ordering disappears for this annealing temperature.

Furthermore, as indicated in Fig. 3, the annealing temperature can strongly affect the composition ratio of the Co and Pt. According to our further AES data (not shown here), a postdeposition annealing at appropriate annealing temperatures (600 K) can form a metastable phase with certain ratio of the Co and Pt composition, which is stable against a long time annealing and is accompanied with a constant magneto-optical optical Kerr effect.

Two characteristic LEED patterns, as shown in Fig. 3, are observed on the unannealed and annealed films. The first one reveals a six fold satellite fine structure around the $p(1 \times 1)$ main spots. This incommensurate LEED pattern is attributed to an incoherent epitaxy of the Co film on the Pt (1 1 1) substrate. Above the 550 K annealing temperature, which is almost the same as the onset annealing temperature of increase in polar remanence Kerr effect, the LEED pattern become $p(1 \times 1)$ with fuzzy spots. The in-plane lattice constant is close to that of the Pt (1 1 1) substrate. Together with the finding of a drop of Co–Pt Auger signal ratio, this structural transformation observed in the LEED pattern indicates a Co–Pt alloy formation at interface. The formation of Co–Pt alloy in this system has been reported in details in our previous study [8]. Corresponding to the structural evolution found in LEED upon thermal annealing, our previous data of ultraviolet photoelectron spectroscopy (UPS) also indicate a significant change in the valence electronic structure, which may be attributed to the formation of Co–Pt bonds associated with a charge transfer between Co and Pt sites [8]. Based on the UPS data and the findings in Fig. 3, one can conclude that the enhancement of magneto-optical Kerr response is correlated with the formation of Co–Pt alloy at interface or surface.

In general, increase in magneto-optical Kerr response may be interpreted as increase in magnetization (this is also why we usually use MOKE to probe the magnetic properties) or enhancement of magneto-optical Kerr effect itself. However, the largely enhanced magneto-optical response, as shown above (up to about 300%), seems unlikely to be due to change in magnetization mainly. Based on the previous experimental report on the composition dependence of the magnetic moment in Co–Pt alloy thin film system [10], the change of magneto-optical response due to increase in magnetization in our case is estimated to be only percent [11]. The correlation of the alloy formation at interface and the enhancement of the magneto-optical Kerr effect may be thus traced backed to the transfer of the strong spin–orbit coupling of the Pt into the magnetic Co orbital due to the hybridized electronic structure, as suggested in the theoretical study for the Co–Pt ultrathin multilayer system [9]. The significant enhancement of the magneto-optical Kerr signal in our case may be due to a special hybridization state between the Co and Pt through the thermal annealing, which is different from the expected structure in the Co–Pt alloy and multilayer systems as usual. This may explain the amazing enhancement factor (300%) of magneto-optical Kerr signal found in our work, as compared to the previous study for the Co–Pt multilayer and Co–Pt alloy system [12].

4. Conclusion

Upon a thermal postdeposition annealing at appropriate temperatures, a giant enhancement of magneto-optical response up to about 300% is observed for the ultrathin Co–Pt (1 1 1) film in monolayer range. This finding is correlated to a Co–Pt alloy formation at interface, which results in a transfer of the strong spin–orbit coupling of the Pt into the Co, and in turn induces enhancement of the magneto-optical Kerr effect. Our results also suggest that the thermal annealing could be an effective postdeposition processing to modify the magneto-optical properties, and may become technologically relevant.

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