Perpendicular magnetic anisotropy in $CoPt_3$ (111) films grown on a low energy surface at room temperature

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INTRODUCTION

Co-Pt binary alloys have been extensively studied. Owing to their strong perpendicular magnetic anisotropy (PMA) they are potential materials for high-density magneto-optical recording [1, 2]. In fcc $Co_xPt_{\{1-x\}}$ films PMA has various causes such as growth-induced heterogeneity, compressive strain, short-range order driven by surface segregation, or magnetically induced phase separation, but it is not linked to the appearance of any chemical long-range ordered phase. The ordered $CoPt_3$ phase ($L1_2$-type) which can be regarded as a chemically ordered fcc structure with Co atoms at the cube corners and Pt atoms at the face centers in the atomic unit cell shows no PMA due to its cubic symmetry. This is also true for the chemically disordered phase where the Co and Pt atoms are randomly distributed on the fcc lattice. Nevertheless, it was previously reported that epitaxial $CoPt_3$(111) films grown on Pt(111) and Ru(0001) at temperatures between 200-400°C exhibit strong PMA and large coercivities as well as no chemical long-range ordering (LRO) [3, 4]. These observations can be explained by structural short-range ordering effects.
We have recently reported [5, 6] that $CoPt_3$(111) films grown on a van der Waals surface of WSe_2(0001) exhibit remarkable properties: strong PMA for deposition temperatures $T_g < 150$°C and the appearance of chemical long-range ordering ($L1_2$-type) at a deposition temperature of about 100°C, which is 400°C lower than observed for $CoPt_3$ films grown on Pt(111) [4]. In this paper we describe the magnetic properties of $CoPt_3$(111) thin films deposited at room temperature on WSe_2(0001) as a function of film thickness.

EXPERIMENT

$CoPt_3$(111) films were grown by molecular beam epitaxy through the co-evaporation of Co and Pt from two e-beam sources at room temperature on WSe_2(0001) single crystals. The surface quality of the substrate was extremely high, showing atomically flat terraces with widths of several microns, as verified by scanning tunneling microscopy (STM). The Co and Pt atomic fluxes gave deposition rates of 0.001 and 0.0043 nm/s, respectively. Film thicknesses were controlled by a quartz-crystal balance and a quadrupole mass spectrometer. Structural characterization was performed by using in-situ reflection high energy electron diffraction (RHEED) and high-resolution x-ray diffraction (XRD). The results from these structural studies are reported elsewhere [5]. The magnetic properties of these films were measured by superconductive quantum interference device (SQUID) and photoemission electron microscopy (PEEM) using the PEEM-2 endstation at beamline 7.3.1. of the ALS [7]. Using monochromatized circularly polarized x-rays and applying x-ray magnetic circular dichroism (XMCD) as the contrast mechanism it is possible to obtain images showing the magnetic state of the sample. Images were acquired at the L_2 and L_3 edges of Co using circularly polarized x-rays incident at the sample at an angle of 30 degrees from the surface. The images were scaled to the same intensity and divided to eliminate topographic contrast and obtain only magnetic contrast.

RESULTS AND DISCUSSION

A series of $CoPt_3(111)$ samples deposited at room temperature with film thicknesses t of 3, 6, and 9 nm were produced. In order to protect the samples against oxidation an additional 2nm thick cap layer of vanadium was deposited. The morphology of these films, investigated by atomic force microscopy, consisted of a dense nanometer-sized grain structure. The average lateral dimension increased from 3nm to 6nm as the film thickness increased from 3 to 9nm. The averaged roughness over the whole surface was estimated to be in the range of up to 0.5nm [5].
We investigated the reorientation of the magnetization from perpendicular to in-plane as a function of film thickness in the range 3 to 9nm using SQUID at room temperature with the field applied either perpendicular or parallel to the plane of the film. The magnetization curves obtained for the 3nm thick $CoPt_3(111)$ film are characteristic of a film with perpendicular anisotropy with a squareness of S=1, a coercivity of 200Oe, a saturation magnetization of M_s=520emu/cm^3 and an effective anisotropy energy of K_{eff}=1.5x10^{6}erg/cm^3. We observed that effective anisotropy energy is reduced considerably by increasing the film thickness. At a film thickness larger than 6nm the easy magnetization axis rotates progressively into the film plane and K_{eff} changes sign.
Strong changes in anisotropy conditions are also reflected in the magnetic domain structure. The domain structure of films exhibiting perpendicular anisotropy was imaged by PEEM. It is worth mentioning that no magnetic contrast was found by magnetic force microscopy (MFM) due to the fact that the magnetic stray field from the MFM tip causes magnetization of the samples to change during the scanning process. Using circularly polarized x-rays and applying x-ray magnetic circular dichroism (XMCD) as the contrast mechanism we obtained images showing the magnetic state of the samples. All images reveal dark and white domains with only two different gray levels as shown in Fig. 1. This and the fact that the contrast of the image does not change when the sample is rotated in-plane are a clear indication that the direction of magnetization in those domains is perpendicular to the surface.

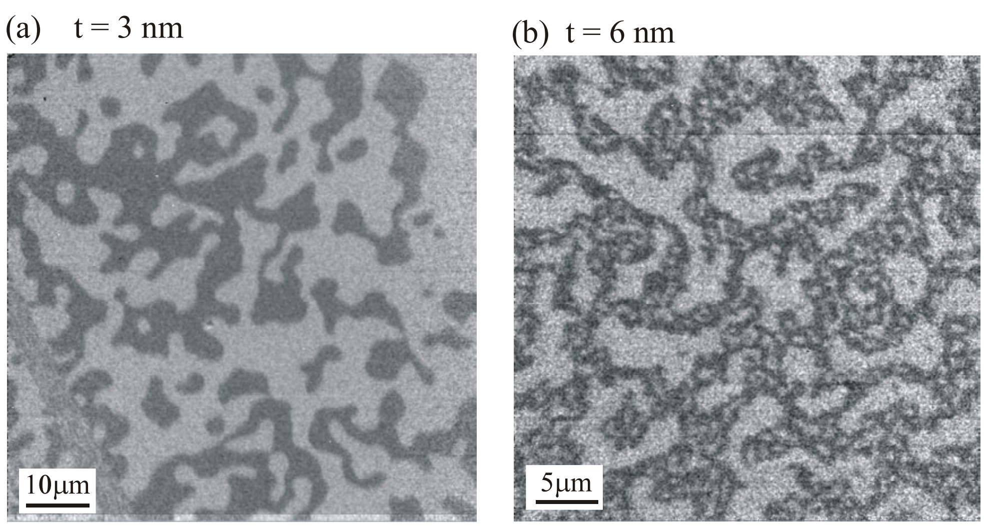

Figure 1. Perpendicular magnetic domain structures of $CoPt_3(111)$ films previously demagnetized out-of-plane with thicknesses (a) 3nm and (b) 6nm obtained by PEEM using XMCD contrast at the Co $L_{2,3}$ edges.

Prior to measurement the samples were demagnetized by exposing the sample to an alternating perpendicular magnetic field with decreasing amplitude, however a small net magnetization remained. The perpendicular domain structures can be characterized as one of two different types. At a film thickness of 3nm we found a domain structure that appears serpentine in nature (Fig. 1(a)). Increasing the film thickness from 3 to 6nm (Fig.1(b)) the averaged domain size decreases from about 8 to 3microns. This decrease at a thickness near the onset of transition to in-plane magnetization is predicted by the theory of domain formation in thin perpendicular films. It is due to the fact that the magnetization can remain perpendicular by decreasing the shape energies via domain creation. In addition, nucleation of magnetic bubbles in the submicron length scale with opposite magnetization starts to fragment the larger domain features. This interior bubble domain structure also leads to a reduction of the magnetostatic energy inside a large domain and is therefore an energetically favorable process.

CONCLUSIONS

It is well known that in thin films growth (particularly for compounds) the choice of the substrate is important because it influences several properties such as surface mobility, growth mode, lattice parameter mismatch, and symmetry. Here we used a special substrate that has a van der Waals surface. On this surface single-crystal growth of (111)-oriented fcc $CoPt_3$ films was obtained even at room temperature. These films show strong perpendicular magnetic anisotropy for a thickness range of up to 6nm combined with an extremely small grain structure and are therefore potentially interesting as data storage media. For larger thicknesses a rotation of the magnetization from perpendicular to in-plane is observed. This reorientation is associated with a change in the magnetic domain structure observed by PEEM. We conclude that in the ultrathin film limit the strong perpendicular anisotropy is induced by some kind of thickness-dependent short-range ordering effects enhanced by the nanometer-sized film morphology. The change of anisotropy is connected with the diminution of short-range ordering as the film morphology changes from a isolated nucleation structure to a continuous material.

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