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Nanostructure and magnetic anisotropy of Co/Au multilayers

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Multilayer Co/Au films were deposited on 40 nm Au underlayer by magnetron sputtering. The Co thickness is kept constant at 0.5 nm while the Au thickness is varied from 0.5 to 8 nm. Magnetic measurements show that the perpendicular anisotropy of the films changes from 3×10^6 to 1.5×10^6 erg/cm^3 as the Au thickness changes from 6 to 1 nm. Two films of (Co 0.5 nm/Au 6 nm)×9/Au 40 nm (denoted Au6) and (Co 0.5 nm/Au 1 nm)×50/Au 40 nm (denoted Au1) were examined by transmission electron microscopy. For the Au6 film, a bright-field image reveals the curvature of the multilayer. High-resolution electron microscopy shows that the curvature consists of many atomic steps leading to a rough interface. The Au layer has the fcc structure (ABCABC stacking) and the Co layer of two atomic layers interrupts the ABCABC stacking of Au and could be fitted to the AB stacking. In contrast to the Au6 film, the Au layers and the Co layers in the Au1 film cannot be identified in the high-resolution electron microscopy image. Bright field transmission electron microscopy images reveal the evidence of local clustering of Au and Co. A high density of $1/3[111]a$ dislocations is observed which supports the clustering argument. The anisotropy of the films is discussed in connection with the observed nanostructure involving the steps and the clustering of Au and Co. © *1997 American Institute of Physics.* [S0021-8979(97)49608-1]

I. INTRODUCTION

Artificial thin films consisting of periodic stacking layers of a magnetic metal and a nonmagnetic metal such as multilayers Co/Y (Y=Pt or Pd, Au, Cu, Ag, Ir) are attracting strong interest.[1] Such films have in-plane anisotropy and perpendicular anisotropy depending on the thickness of the magnetic layer. The anisotropy of the films changes from in plane to the perpendicular direction as the thickness of the Co layer reduces to a critical value.[2,3] The films of perpendicular magnetic anisotropy and significant Kerr rotations have potential as high-density magneto-optic storage media. Defect structures such as the roughness of the interface[4] and the degree of mixing of the atoms at the interface (the sharpness of the interface)[5] have been found to affect the anisotropy. This article reports the relationship between the nanostructure and the magnetic properties of the films with the same Co thickness of 0.5 nm but different Au thicknesses from 0.5 to 6 nm. The focus is on the evolution of the nanostructure as the Au layer becomes thinner. Details of the film deposition and transmission electron microscopy (TEM) sample preparation can be found in Ref. 6.

II. RESULTS

Figure 1 shows the magnetization loops for the three films (Co 0.5 nm/Au 0.5 nm)×50/Au 40 nm (denoted Au 0.5), (Co 0.5 nm/Au 1 nm)×50/Au 40 nm (denoted Au1), and (Co 0.5 nm/Au 6 nm)×9/Au 40 nm (denoted Au6). The films Au0.5 and Au1 show an irregular perpendicular magnetization loop with $S=0$ (S is defined to be m_r/m_s), while the film Au6 shows a well-defined perpendicular magnetization loop with loop squareness $S=1$. The magnetic anisotropies were measured by the area bounded by the perpendicular loop and the in-plane loop. Values of 1.5×10^6 erg/cm^3 for Au1 and 3×10^6 erg/cm^3 for Au6 were obtained. These values are in the same order but slightly lower than those obtained by other researchers.[5]

Figure 2 shows the TEM bright field micrograph of the Au6 film. The grain size of the Au underlayer is about 50 nm. Slight curvature of the multilayers is observed. The curvature is inherited from the surface of the underlayer. Both nanodiffraction and high-resolution electron microscopy (HREM) show that the multilayers are epitaxially grown on the Au underlayer. Figure 3 shows a [110] zone axis HREM image of the Au6 film. The Au layers and the Co layers can be identified by their different stacking mode. The Au layers have the ABCABC stacking with frequent twins. The letter *t* indicates a twin. The two atomic Co layers interrupts the ABCABC stacking of Au and could be fitted to the AB stacking as indicated by the arrows. The formation mechanism of the curvature of the multilayer is clearly revealed.
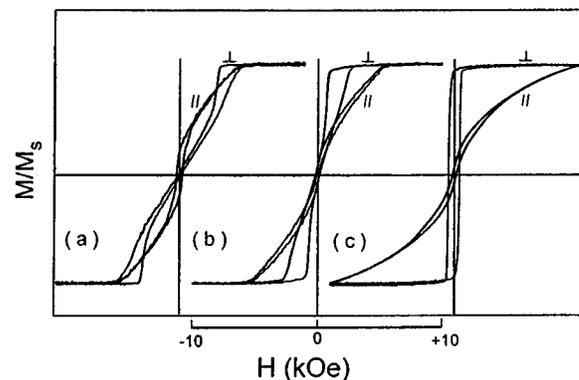

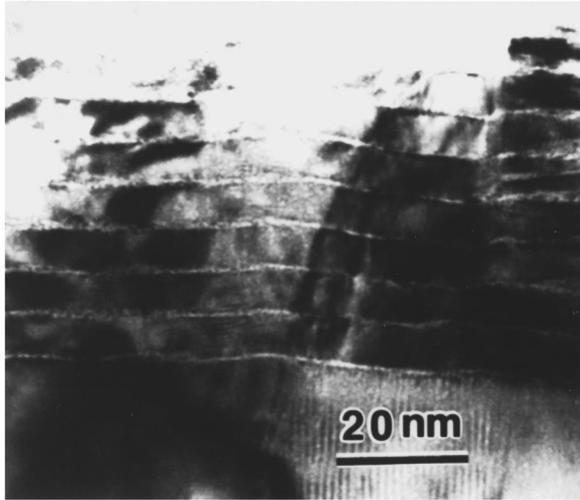FIG. 1. Magnetization loops of (a) Au 0.5 film, (b) Au1 film, (c) Au6 film.

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FIG. 2. Bright field TEM image of the Au6 film.

FIG. 4. Bright field TEM image of the Au1 film.

That is, the curvature is formed by many atomic steps rather than the bending of the atomic planes.

Figure 4 is the bright field image of the Au1 film. The Au layers and the Co layers can be differentiated from each other by their different contrast. The Au layers appear dark because of their larger electron scattering factor. A careful examination indicates that the multilayer structure is frequently interrupted by local clustering which appears darker or brighter as indicated by the arrows. The cluster size is in the range of 2–4 nm. Figure 5 is an example of many [110] zone axis HREM images taken from the Au1 sample. The close-packed atomic planes are resolved in most parts of the image; however, the Au layers and the Co layers in the HREM image cannot be differentiated. Local ABC stacking, which is an indication of Au atom clusters, and local ABAB
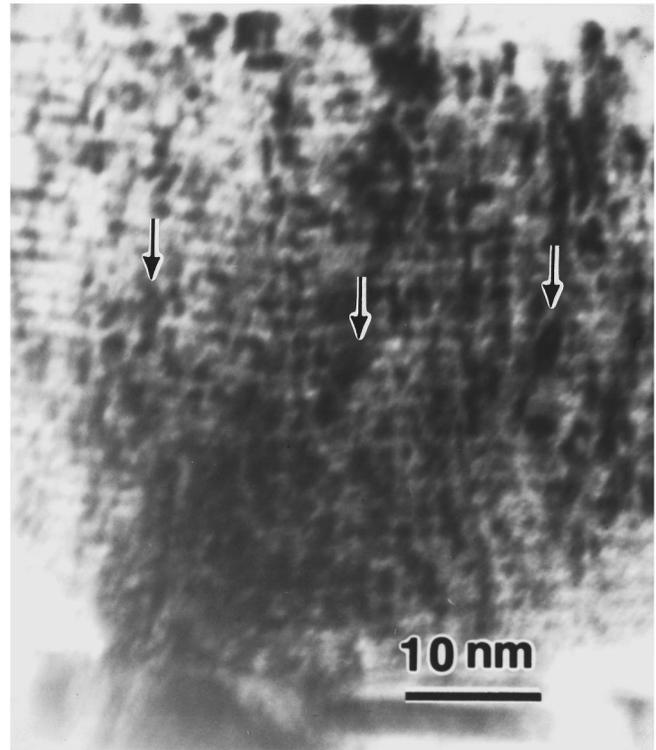
stacking, which is an indication of Co clusters, are observed. $1/3[111]a$ dislocations are frequently observed. One example is indicated by the arrow. The lattice spacing mismatch between Au and Co in the [111] direction of Au is $d_{Au}(111) - d_{Co}(0001) = 0.2355 - 0.2032 = 0.0323$ nm. This mismatch favors the formation of the $1/3[111]a$ dislocations if local Au clusters and Co clusters exist.

III. DISCUSSION

The most significant difference between the two films is that the multilayer structure in Au1 film is replaced partially
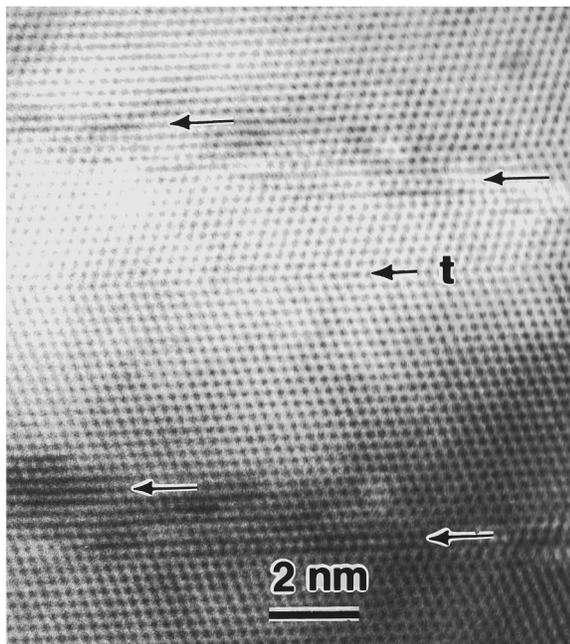

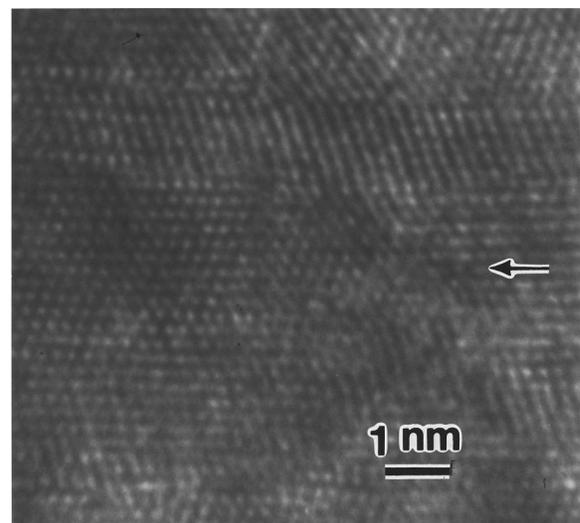FIG. 3. [110] zone axis HREM image of the Au6 film.

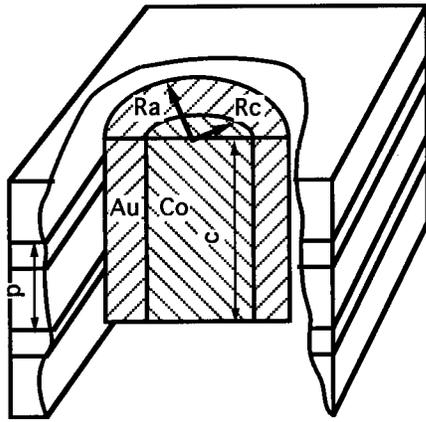FIG. 5. [110] zone axis HREM image of the Au1 film.

FIG. 6. Schematic illustration of the formation of a cluster in the multilayer film.

by clusters of Au atoms and clusters of Co atoms. Such clusters could be configured in a random fashion. When two clusters of Au and Co overlap in the direction of observation, the HREM image will be significantly blurred which is believed to be the case for the Au1 specimen. Such clusters significantly reduce the interface area parallel to the film surface. A simple cluster model is used to estimate the reduction of the interface area. Supposing a volume V_c multilayer is transformed to clusters, the lost interface parallel to the film surface is $2V_c/p$, where p is the period length of the multilayer. The interface area of a perfect multilayer of volume V is $2V/p$. The ratio of lost interface area to the interface area in the multilayer is V_c/V. Therefore, cluster formation significantly reduces the interface area and therefore reduces perpendicular anisotropy.

There are no compounds found in the Au–Co phase diagram, indicating a high-energy state of the Au–Co atomic pairs. Therefore a positive Au–Co interface energy is expected. If the formation of Au and Co clusters can reduce the interface, the clusters will be stable relative to the multilayer structure. Let us consider a simple model for morphology transformation sketched in Fig. 6. Supposing a Co cylinder cluster of radius R_c and a Au cylinder cluster of radius R_a coaxially grow in the multilayer, the interface areas in the cylinder of radius R_a before transformation A_1 and after transformation A_2 are

$$A_1 = 2\pi c R_a^2/p, \tag{1}$$

$$A_2 = 2\pi(cR_c + ct_cR_a/p + R_c^2), \tag{2}$$

respectively, where c is the height of the cluster, p the period length of the multilayer, and t_c the thickness of Co layer. R_c is related to R_a by the volume ratio of Co against Au to be $R_c = R_a/(t_a/t_c+1)^{1/2}$; letting $A_1 = A_2$, we have the critical R_0 corresponding to R_a at $A_1 = A_2$ to be

$$R_0 = (1/m + t_c/p)/[1/p - 1/cm^2], \tag{3}$$

where $m = (t_a/t_c+1)^{1/2}$ and t_a is the thickness of Au layer. For Au1 film, $t_a = 1$, $t_c = 0.5$, $p = 1.5$, and letting $c = 4p = 6$, we have $R_0 = 1.49$. For Au6 film, $t_a = 6$, $t_c = 0.5$, $p = 6.5$, and letting $c = 6.5$, we have $R_0 = 2.49$. The above result indicates that the Au6 film has a larger critical cluster radius R_0 than the Au1 film. The actual cluster dimension must be larger than R_0 in order for the morphology transformation to have enough driving force. A larger cluster dimension encounters larger energy barrier and longer diffusion distance in its formation process. Since a thicker Au layer film has larger critical radius, morphology transformation in thicker Au layer films is more difficult than in thinner Au layer films.

IV. CONCLUSIONS

(1) In films with Au layer equal and thicker than 2 nm, well-defined perpendicular loops are obtained and the films exhibit perpendicular anisotropy of 3×10^6 erg/cm^3. Bright field and high-resolution TEM study indicates that the Au layers and the Co layers can be identified from each other and the multilayer structure is sustained throughout the whole film. However, terraces consisting of atomic steps leading uphill, a flat area, and then atomic steps leading downhill are observed at the interface. Such kind of terraces are inherited from the Au underlayer which receives the surface undulation of the substrate.

(2) The perpendicular anisotropy decreases from 3×10^6 to 1.5×10^6 erg/cm^3 as the thickness of Au layer reduces 1 nm. Bright field TEM images indicate that the multilayer structure is interrupted by the formation of local clusters of Au and Co. The formation of such clusters results in reduction of the Au–Co interface parallel to the surface and introduction of random interfaces which is responsible for the low values of the perpendicular anisotropy of the film.

(3) A simple geometric model taking account of interface area indicates that the clusters are stable relative to the multilayer structure if the size of the clusters is larger than a critical value. Thicker Au layer films have higher energy barrier and longer diffusion distance for the formation of cluster structure and therefore are more stable than thinner Au layer films.

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