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The temperature dependence of the sputtering Ar pressure effects on magnetic properties and the coercivity mechanism of Co(2 Å)/Pd(13 Å) multilayers were studied as the sputtering Ar pressure varied from 3–15 mTorr and the temperature from 300 to 35 K. It is found that the roughness of the interfaces or film surface increases with increasing sputtering pressure, the anisotropy increases with decreasing temperature and increasing Ar pressure and shows a maximum at $P_{Ar}\approx 12$ mTorr, and the coercivity increases with Ar pressure and shows stronger temperature dependence at higher Ar pressure. The coercivity mechanism was analyzed in terms of the coercivity predicted by Kronmüller's theory [Phys. Status Solidi B **144**, 385 (1987)]. Wall pinning is found to be the main mechanism and the size of the pinning site increases slightly as the Ar pressure increases.

I. INTRODUCTION

Co/Pd multilayers have been studied intensively in the last decade for pure and applied reasons.[1–3] For the Co/Pd multilayers with nanoscale Co layer, the interfacial magnetism, which is strongly influenced by the preparation conditions, plays a crucial role in determining the magnetic behavior. Hashimoto *et al.*,[4] de Haan *et al.*,[5] Shin *et al.*,[6] and He *et al.*[7] have reported the Ar pressure effects on magnetic properties at room temperature. It is found that the coercivity increases with increasing Ar pressure P_{Ar} during deposition and the anisotropy increases monotonically with increasing P_{Ar} (up to $P_{Ar}\approx 56$ mTorr),[5] or shows a maximum at $P_{Ar}=10$ mTorr.[4,6]

In this article the temperature dependence of the sputtering pressure effects on magnetism was studied as the temperature varied from 300 to 35 K. The coercivity mechanism was investigated in terms of the initial magnetization curves and minor loops at different temperatures, and comparisons were made to Kronmüller's model.[8]

II. EXPERIMENT

[Co(2 Å)/Pd(13 Å)]×35 (35 is the number of bilayers) multilayers were deposited onto glass substrates by dc magnetron sputtering under pressure $P_{Ar}=3$, 6, 9, 12, and 15 mTorr. All five samples were fabricated in one vacuum run to insure identical preparation conditions except for the Ar pressure.

The structure properties were characterized with the x-ray diffraction and atomic force microscopy (AFM) and the magnetic properties were measured by an alternating gradient force magnetometer (AGFM) with the temperature changed from 300 to 35 K. The coercivity $H_c(T)$ and magnetization $M(T)$ data were obtained from the perpendicular hysteresis loops and the measured anisotropy $K_u'(T)$ data were determined from the area between the parallel and perpendicular magnetization curves.

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III. RESULTS AND DISCUSSIONS

A. Structure properties

Figure 1 shows the small-angle x-ray-diffraction patterns. It is seen clearly that the amplitude of the diffraction peaks decreases with increasing sputtering Ar pressure and when the sputtering pressure is greater than 9 mTorr, the diffraction peaks become obscure. This is attributed to the roughness of the interfaces which increases as the sputtering pressure increases since the sputtered Co and Pd atoms experienced more collisions with Ar atoms and form larger clusters at the growing film surface.

Figure 2 shows the AFM pictures of samples sputtered at (a) $P_{Ar}=3$ mTorr and (b) 15 mTorr and it is found that the surface roughness in Fig. 2(b) is much larger than that in Fig. 2(a). If the surface roughness may be regarded as the accumulation of the roughness of all individual layers or interfaces, Fig. 2 indicates clearly that the interfaces have larger roughness when sputtered in the higher Ar pressure, which is consistent with the result in Fig. 1.

B. Temperature character of pressure effects on magnetic properties

The Ar pressure dependence of the anisotropy K_u ($K_u = K_u' + 2\pi M_s^2$) as the temperature varied from 300 to 35 K is demonstrated in Fig. 3. It is seen that K_u increases as the temperature decreases. As the pressure increases K_u first increases, then decreases and shows a small peak at $P_{Ar}=12$ mT for all temperatures. This behavior is qualitatively consistent with earlier work[4,6] except that our peaks are rather small; K_u shows larger Ar pressure dependence at lower temperature. The origin of such K_u behavior is attributed to the interfacial magnetism which strongly depends on the polarization of Pd atoms at the interfaces[9,10] and the morphology of interfaces. As the temperature decreases the induced Pd moment increases which enhances the K_u. Hashimoto and co-workers[4] have explained qualitatively the behavior of Ar pressure dependence of K_u in terms of the stress-induced anisotropy because the stress in the film changes from compressive to tensile as the Ar pressure increases. Recently Vic-

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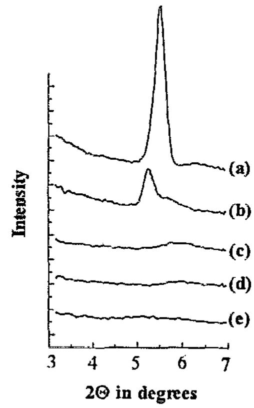

FIG. 1. Small-angle x-ray diffraction for Co(2 Å)/Pd(13 Å) deposited at different Ar sputtering pressures: (a) 3 mTorr; (b) 6 mTorr; (c) 9 mTorr; (d) 12 mTorr; and (e) 15 mTorr.

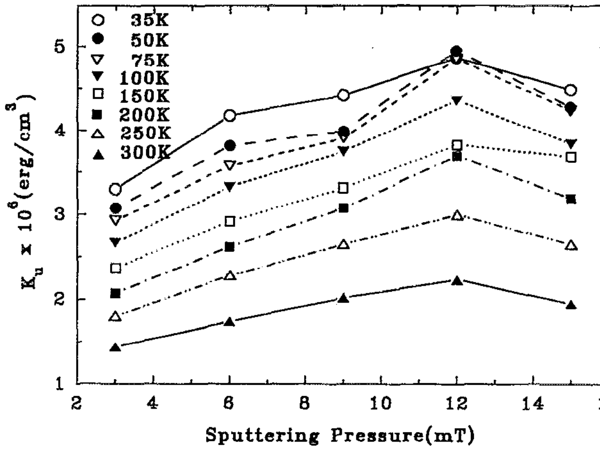

FIG. 3. Sputtering Ar pressure dependence of measured anisotropy K_u' at different temperatures.

tora and MacLaren[11] employed the symmetry-derived model based on summing $L(\mathbf{M}\cdot\mathbf{R})^2$ pair interactions (where $\mathbf{M}$ is the magnetization direction, $\mathbf{R}$ is the vector connecting the two atoms, and L is an interaction parameter) to calculate anisotropy for Co/Pd and Co/Pt multilayers. We intend to use this approach to calculate the K_u behavior quantitatively.

The sputtering pressure dependence of coercivity H_c as the temperature varied from 300 to 35 K is shown in Fig. 4(a). The coercivity increases monotonically with increasing P_{Ar} and shows stronger P_{Ar} dependence at the lower temperature. This behavior cannot be attributed fully to the change of K_u as shown in Fig. 3. In order to understand such behavior properly, we also need to consider the pinning effect of the domain-wall motion which is discussed in more detail in the following section.

The temperature dependence of H_c is shown in Fig. 4(b): H_c increases as the temperature decreases and shows stronger temperature dependence at higher P_{Ar}. The physical origins of this feature are discussed below.

C. Coercivity mechanism

In order to study the coercivity mechanism the initial curves and minor loops were measured at room and low temperature. All these curves show the typical domain-wall pinning feature: The magnetization is small at low applied field H_a and increases rapidly while H_a reaches a threshold value H_{th} which corresponds to the field required to exceed the pinning barrier. As the temperature decreases the thresh-

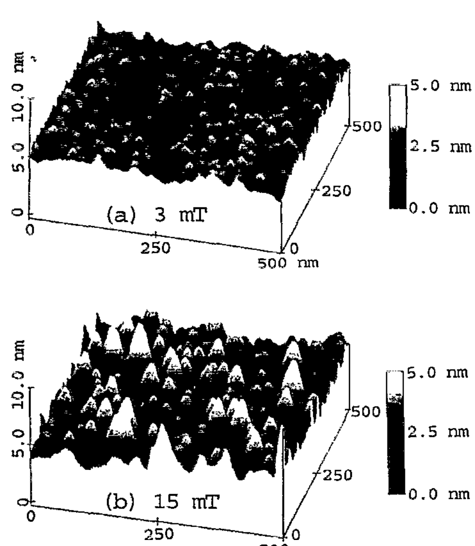

FIG. 2. AFM micrographs of Co(2 Å)/Pd(13 Å) deposited at Ar sputtering pressure of: (a) 3 mTorr and (b) 15 mTorr.

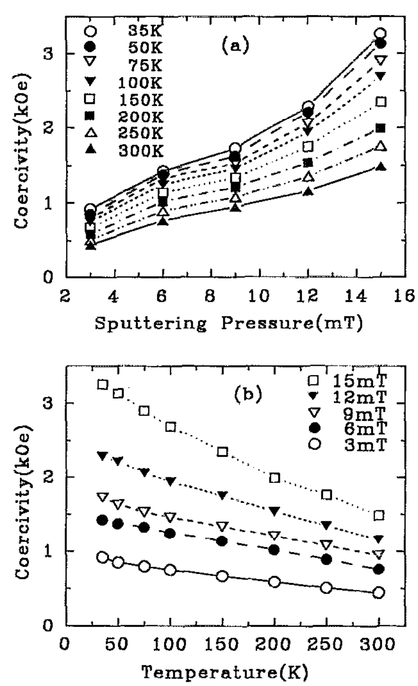

FIG. 4. (a) Sputtering Ar pressure dependence of coercivity at different temperature and (b) temperature dependence of coercivity at different sputtering Ar pressure.

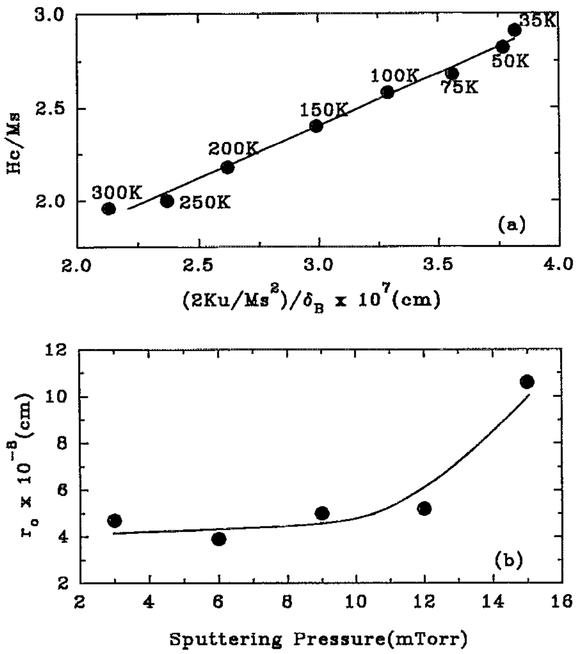

FIG. 5. (a) A linear fitting to the experimental data after Eq. (1) and the r_0 obtained is 4.7 Å. (b) The sputtering Ar pressure dependence of the estimated size of the pinning site.

old field H_{th} increases because of the decreasing thermal activation energy as predicted by Kirby *et al.*[12]

Kronmüller's formulas[8] were used to analyze the coercivity mechanism in more detail. If wall pinning is the dominant mechanism, the coercivity $H_c(T)$ is given by

$$H_c(T)=\kappa(r_0/\delta_B)(2K_u/M_s)-N_{\text{eff}}M_s \quad \text{for} \quad r_0 \ll \delta_B \qquad (1)$$

and

$$H_c(T)=\kappa'(\delta_B/r_0)(2K_u/M_s)-N_{\text{eff}}M_s \quad \text{for} \quad r_0 \gg \delta_B, \qquad (2)$$

where κ and κ' are both related to the exchange coupling constants and the anisotropy constants, r_0 is the size of the pinning site, and N_{eff} is a demagnetization factor. The wall width δ_B is given by $\pi(A/K)^{1/2}$, where A and K are exchange constant and anisotropy,[13] respectively.

Figure 5 is an example of the fitting curve based on Eq. (1) for the sample prepared at 3 mTorr Ar pressure. Similar fittings for all samples (P_{Ar}=6, 9, 12, and 15 mTorr) have been performed. The fact that the $[H_c/M_s, (2K_u/M_s^2)/\delta_B]$ experimental points measured at different temperatures are on a straight line implies that the domain-wall pinning is the dominant mechanism.

From the fits we could estimate the size of the pinning sites for each sample. The estimated sizes are 4.7, 3.9, 5.0, 5.2, and 10.6 Å for the samples prepared at P_{Ar}=3, 6, 9, 12, and 15 mTorr, respectively [see Fig. 5(b)]. The estimated values show that the size of the pinning site increases with increasing sputtering pressure. Equation (1) also tells us that $H_c(T)$ depends on the r_0K_u product. Although K_u decreases with increasing P_{Ar} for P_{Ar}>12 mTorr (as shown in Fig. 3), H_c still increases with increasing P_{Ar} for P_{Ar}>12 mTorr [as shown in Fig. 4(a)] because r_0 increases, and we have pointed out this feature earlier.

IV. CONCLUSIONS

The variation of the anisotropy and coercivity as a function of temperatures is closely related to the polarization of the Pd atoms at the interfaces and the film morphology which was controlled by the sputtering Ar pressure. The dominant mechanism for the coercivity is the wall pinning and the size of the pinning sites increase with increasing the sputtering pressure.

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