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Behavior of disordered Co-Pd, Co-Ag, and Co-Mo alloys in multilayer interfaces

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Local environment effects are important for understanding interfacial magnetism in artificially structured multilayers. For this reason, stable and/or metastable disordered alloys Co_XM_{1-X} (M=Pd, Ag, Mo) were fabricated in a dc cosputtering system. The magnetization as a function of composition and temperature were measured and analyzed in terms of a mean-field model. The local environment effect on the Co moment from its Ag (or Mo) neighbors and the Pd moment from its Co neighbors are studied. It is found that the polarized Pd moment increases linearly with an increasing number of nearest Co neighbors and the Co moment is destroyed by only two Mo neighbors.

I. INTRODUCTION

It is well known that Co/M (M=Pd, Pt) multilayers, where the Co layer is only one or a few atomic layers thick, display strong perpendicular magnetic anisotropy (PMA).[1-3] Phenomenologically, PMA is attributed to the interfacial magnetism, which is characterized by the broken symmetry of the constituent atoms. The origin of PMA has been studied actively in recent years, and it has been suggested that the sharp interfacial boundary and strain between the Co and M layers favors the creation of PMA.

However, multilayers of Co/Ag and Co/Mo do not show PMA at all,[1,4] even though they have a rather sharp interfacial boundary and their lattice mismatch is significant (~ 0.15). Usually this is imputed to the very rough interface due to poor wetting between the constituents.[1]

The structural properties of equilibrium Co-M (M =Pd, Ag, Mo) alloys can be found in the phase diagrams of Ref. 5. The magnetic behavior of Co-Pd at 7 K has been reported in Ref. 6 and Co-Mo at room temperature for Mo at. $\% < 3\%$ in Ref. 7. In this article, stable or metastable disordered Co_XM_{1-X} (M=Pd, Ag, Mo) alloys were prepared by the sputtering technique and their magnetic properties were investigated systematically for $0.16 < X < 0.9$ at $T=5$ and 300 K.

The main goal of the present article is to probe the local-environment effect on atomic moments and subsequently the behavior of the corresponding magnetic multilayers.

II. EXPERIMENT

Co_XM_{1-X} were prepared in a dc cosputtering system with a base pressure of 8×10^{-8} Torr and the Ar pressure during sputtering of 5×10^{-3} Torr. Structural studies were performed by x-ray diffractometry using a Cu$K\alpha$ target and the magnetic properties were characterized by the alternating gradient magnetometer (AGM) and superconducting quantum interference device (SQUID) from 5 to 380 K.

III. STRUCTURE

Examples of x-ray-diffraction patterns for Co-Pd, Co-Ag, and Co-Mo are shown in Fig. 1 and the interlayer spacing corresponding to the first and second peaks as a function of Co at % is shown in Fig. 2. The x-ray diffraction showed the following.

(i) For Co_XPd_{1-X}, both Co and Pd have the fcc structure and they form a disordered solution. The (111) and (200) interlayer spacings vary smoothly with Co atomic fraction as seen in Figs. 2(a) and 2(b).

(ii) For Co_XAg_{1-X}, there exists a two-phase system consisting of essentially fcc Ag plus Co-rich fcc Co-Ag disordered alloy; therefore, the interlayer spacing of Ag(111) is independent of X [Fig. 2(a)] and the interlayer spacing of Co-rich Co-Ag(111) approaches the Co(111) value as X increases [Fig. 2(b)].

(iii) For Co_XMo_{1-X}, as X increases the interlayer spacing of the only peak corresponding possibly to the mixture of Mo-rich Mo-Co(110) and Co-rich Co-Mo(111) decreases and varies from the Mo(110) to the Co(111) value indicating a disordered solid solution.

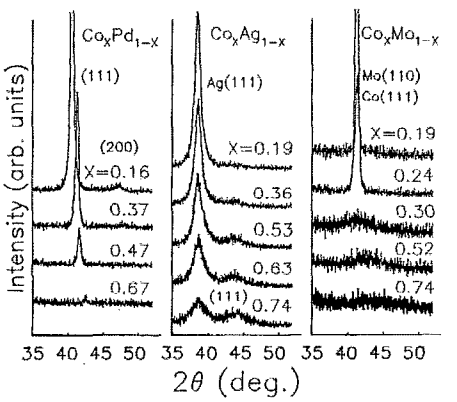

FIG. 1. X-ray-diffraction patterns for Co_XPd_{1-X}, Co_XAg_{1-X}, and Co_XMo_{1-X} disordered alloys.

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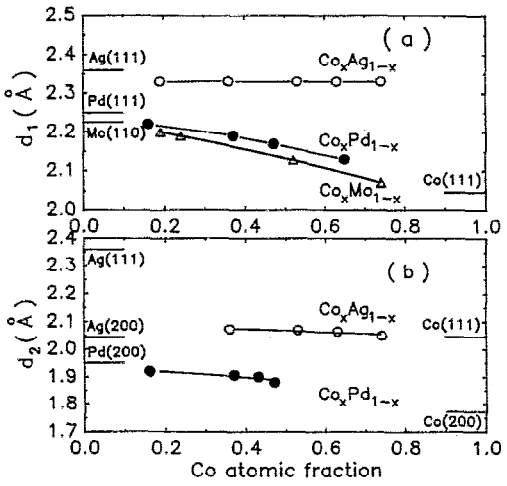

FIG. 2. (a) Interlayer spacing of the first peaks in Fig. 1 as a function of Co atomic fraction and (b) second peaks in Fig. 1 as a function of Co atomic fraction.

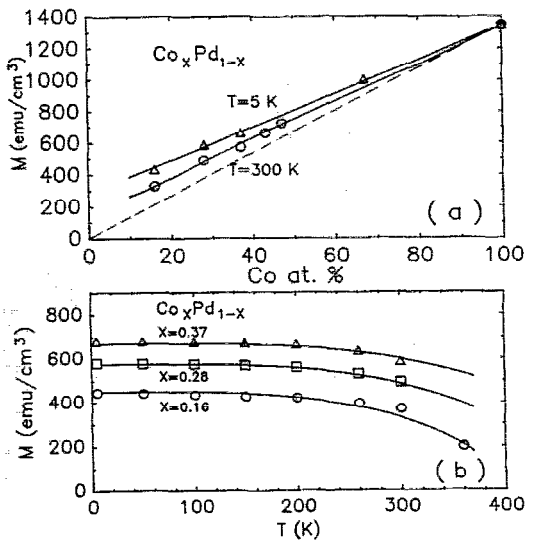

FIG. 4. The comparison between the calculated and experimental magnetization as a function of (a) Co at. % and (b) temperature T. The solid lines are the calculated curves and the spots are the experimental data.

IV. MAGNETIC PROPERTIES

A. Magnetization and mean-field model

1. Temperature and compositional dependencies of magnetization

The spontaneous magnetizations for Co-Pd, Co-Ag, and Co-Mo alloys are summarized in Figs. 3 and 4.

The dashed line in Figs. 3 and 4(a) denotes that the Co constituent possesses the pure Co moment and the other component does not contribute any moment.

It is seen from Fig. 3 that the magnetization curves of Co-Pd ($M_{\text{Co-Pd}}$) are above the dashed line, and $M_{\text{Co-Ag}}$ and $M_{\text{Co-Mo}}$ are below the dashed lines, especially the $M_{\text{Co-Mo}}$ is far below the dashed line. This indicates that in the case of Co-Pd alloys the Pd is polarized which was first pointed out in Ref. 6 at 7 K, and in the case of Co-Ag and Co-Mo alloys, not only Ag and Mo are nonmagnetic; the moment of Co atoms is reduced by the local environmental effect from its nearest neighbors of Ag (or Mo) atoms.

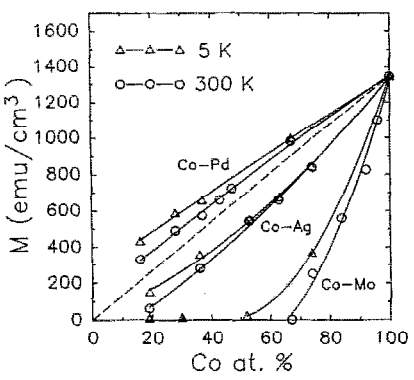

FIG. 3. The compositional dependence of magnetization for Co_XPd_{1-X}, Co_XAg_{1-X}, and Co_XAg_{1-X} at 5 and 300 K.

2. Mean-field analysis

The above experimental results can be analyzed in terms of a mean-field model.[8,9] The calculated results for Co_XPd_{1-X} are shown in Figs. 4(a) and 4(b). The parameters used for calculation are as follows: The exchange constants of Co-Co, Co-Pd, and Pd-Pd are 1.5×10^{-14}, 6.6×10^{-15}, and 1.0×10^{-14} erg, respectively, and the effective Co and Pd atomic moments are 1.62 and $(0.45+0.36X)$ μ_B for $X\geqslant0.15$, respectively. We notice that the calculated result agrees with the experimental data fairly well over the full composition range from 5 to 300 K.

For Co_XMo_{1-X} alloys, the Mo atomic moment is zero and the Co atomic moment is a function of X, which will be discussed in next paragraph. Similar agreement between the experimental data and calculated result has been obtained; however, this figure is omitted for lack of space.

B. Atomic moment and local-environment effect

The local-environment effect is investigated in terms of the Kouvel model[10] for disordered alloys. For Co_XM_{1-X}, the Co and M atomic moment, $\bar{\mu}_{\text{Co}}(X)$ and $\bar{\mu}_{\text{M}}(X)$, are expressed as

$$\bar{\mu}_{\text{M}}(X)=a_0'+a_1'X+a_2'X^2+a_3'X^3+\cdots,$$

$$\bar{\mu}_{\text{Co}}(X)=b_0'+b_1'(1-X)+b_2'(1-X)^2+b_3'(1-X)^3+\cdots, \quad (1)$$

where a_i' and b_i' ($i=0, 1, 2, 3,\cdots$) are the coefficients of the power series. These coefficients are determined from the data in Fig. 3. The Co (or M) atomic moment as a function of the number of its nearest M (or Co) atoms, $\bar{\mu}_{\text{Co}}(n_M)$ and $\bar{\mu}_{\text{M}}(n_{\text{Co}})$, can be expressed as

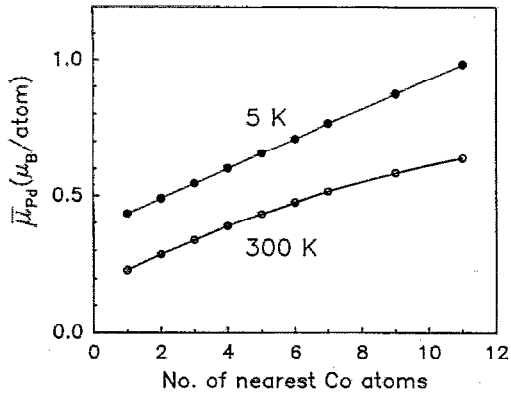

FIG. 5. The Pd atomic moment as a function of the number of its nearest Co atoms.

$$\bar{\mu}_M(n_{Co}) = a_0' + a_1' \frac{n_{Co}}{N} + a_2' \frac{n_{Co}(n_{Co}-1)}{N(N-1)} + \cdots ,$$
$$\bar{\mu}_{Co}(n_M) = b_0' + b_1' \frac{n_M}{N} + b_2' \frac{n_M(n_M-1)}{N(N-1)} + \cdots , \quad (2)$$

where n_{Co} and n_M (M=Pd, Ag, Mo) are the number of the nearest Co and M atoms, respectively, and N is the coordination number of nearest atoms which is taken to be 12 in our alloys.

A summary of the calculated $\bar{\mu}_{Pd}(n_{Co})$ and $\mu_{Co}(n_M)$ (M=Pd, Ag, Mo) are presented in Figs. 5 and 6. It is worthwhile mentioning the following.

(i) For Co-Pd alloys, the polarized Pd moment $\bar{\mu}_{Pd}(n_{Co})$ increases linearly with the number of the nearest Co neighbors (see Fig. 5).

(ii) For Co-Mo alloys, $\bar{\mu}_{Co}(n_{Mo})$ decreases rapidly both at 5 K and 300 K. A surprising result is that the Co atomic moment is destroyed by only as little as two Mo neighbors [see Fig. 6(b)].

(iii) For Co-Ag alloys, a theoretical analysis is very problematic because of the two-phase character of the system as mentioned before. However, if one simply ignores this problem and treats the system as homogeneous, the analysis indicates that $\bar{\mu}_{Co}(n_{Ag})$ decreases with an increasing number of nearest Ag atoms [see Fig. 6(b)].

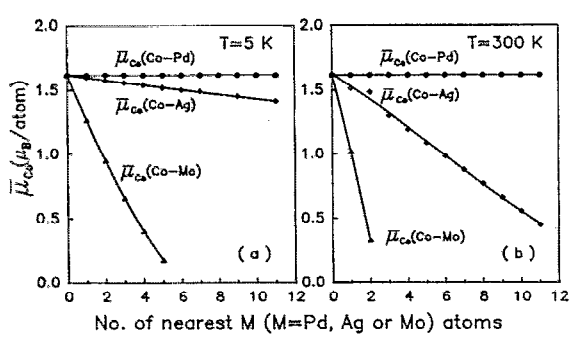

FIG. 6. The Co atomic moment as a function of the number of its nearest M atoms (M=Pd, Ag, Mo).

It should be mentioned that Refs. 11–13 have investigated the "interface dead layers" for Cu/Ni, Co/Ti, and Co/Cu multilayers, respectively. The origin of these dead layers may be understood in terms of the local-environment effect on moments.

V. SUMMARY

In summary the temperature and compositional dependencies of magnetization for Co-M (M=Pd, Ag, Mo) alloys have been measured and analyzed by the mean-field model. The studies of the local-environmental effect on Co and M atoms reveal that for Co-Pd the polarized Pd moment increases linearly with an increasing number of the Co neighbors under the assumption of stable Co moment, and for the Co-Ag and Co-Mo cases, the Co moment decreases with an increasing number of Ag or Mo neighbors. Up to the present time, fundamental theoretical calculations of magnetic anisotropy in multilayers have assumed perfect boundaries with no atomic disorder. In the present work on disordered alloys a clear difference in local-environment behavior has been seen in Co-Ag and Co-Mo contrasted with Co-Pd. Whether this difference can be correlated with the absence or presence of perpendicular magnetic anisotropy in the corresponding multilayers remains to be determined by theoretical calculations that include the effects of atomic disorder at interfaces and local-environment effects such as moment stability.

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[1] F. J. A. den Broeder, W. Hoving, and P. J. H Bloemen, J. Magn. Magn. Mater. **93**, 562 (1991).
[2] P. F. Carcia, A. D. Meinhaldt, and A. Suna, Appl. Phys. Lett. **47**, 178 (1985).
[3] B. N. Engel, C. D. England, R. A. Van Leeuwen, M. H. Wiedmann, and C M. Falco, Phys. Rev. Lett. **67**, 1910 (1991).
[4] N. Sato, J. Appl. Phys. **63**, 3476 (1988).
[5] T. B. Massalski, H. Okamoto, P. R. Subramanian, and L. Kacprzak, Eds. *Binary Alloy Phase Diagrams* (ASM International, Materials Park, OH, 1990); M. Hansen, Ed., *Constitution of Binary Alloys* (McGraw-Hill, New York, 1958).
[6] R. M. Bozorth, P. A. Wolff, D. D. Davis, V. B. Compton, and J. H. Wernick, Phys. Rev. **122**, 1157 (1961).
[7] C. Sadron, Ann. Phys. (NY) **17**, 371 (1932).
[8] R. Hasegawa, J. Appl. Phys. **46**, 5263 (1975).
[9] Z. S. Shan, D. J. Sellmyer, S. S. Jaswal, Y. J. Wang, and J. X. Shen, Phys. Rev. B **42**, 10 446 (1990).
[10] J. Kouvel, in *Magnetizsm and Metallurgy*, edited by A. E. Berkowitz and E. K. Kneller (Academic, New York, 1969), Vol. 2, p. 523.
[11] G. Xiao and C. L. Chien, J. Appl. Phys. **61**, 4061 (1987).
[12] R. V. Leeuwen, C. D. England, J. R. Dutcher, and C. M. Falco, J. Appl. Phys. **67**, 4910 (1990).
[13] S. Nafis, J. A. Woollam, Z. S. Shan, and D. J. Sellmyer, J. Appl. Phys. **70**, 6050 (1991).