Fabrication of L11-type (Co-Ni)-Pt ordered alloy films by sputter deposition

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Fabrication of $L1_1$-type (Co–Ni)–Pt ordered alloy films by sputter deposition

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$L1_1$-type (Co–Ni)–Pt ordered alloy perpendicular films were successfully fabricated on MgO(111) single crystal substrates using ultrahigh vacuum sputter film deposition; the addition of Ni to Co–Pt was effective to reduce saturation magnetization, M_s, maintaining a large K_u of the order of 10^7 erg/cm^3. $L1_1$-type ordered structures, with the ⟨111⟩ direction (easy axis of magnetization) perpendicular to the films, were successfully fabricated at a substrate temperature of 360 °C in a wide composition range with Co content less than 60 at. %. The order parameter, S, was almost a constant of about 0.5 in the stoichiometric composition of $(Co_{1-X}Ni_X)_{50}Pt_{50}$, independent of Ni content, X. $L1_1$-type Co–Ni–Pt perpendicular films having a large K_u of $(1-2.5)\times 10^7$ erg/cm^3 and a relatively low M_s of 400–700 emu/cm^3 were successfully fabricated in the composition range of 10–35 at. % Co, 20–55 at. % Ni, and bal. Pt. K_u should increase further with enhanced ordering. Experimental results demonstrated the potential of these Co–Ni–Pt ordered films for use in data storage applications due to very high K_u potential comparable to $L1_0$-type $Fe_{50}Pt_{50}$ films, relatively low M_s, the relatively low fabrication temperature, and good controllability of the grain orientation.
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I. INTRODUCTION

A large uniaxial magnetic anisotropy energy, K_u, of the order of 10^7 erg/cm^3 is required for bit patterned media with recording densities of multiple terabit per square inch. Two ordered crystal structures having K_u of the order of 10^7 erg/cm^3 have been reported for Co–Pt binary alloys, in addition to the $L1_0$ order structure formed at around $Co_{50}Pt_{50}$ composition, and these structures are shown in Fig. 1. One is a modified $D0_{19}$-type (m-$D0_{19}$) order structure formed at around $Co_{75}Pt_{25}$ composition,[1–3] the other is a $L1_1$-type order structure formed at around $Co_{50}Pt_{50}$ composition.[4–6] These two phases are quasistable, however, they can be formed at relatively low substrate temperatures of 300–400 °C. This temperature is much lower than that required for the $L1_0$ order structure (above 600 °C). Moreover, the easy axes of magnetization for m-$D0_{19}$ and $L1_1$-type ordered structures are perpendicular to the close-packed planes of these structures, which would result in a good controllability of the grain orientation for perpendicular anisotropy films. It is likely that m-$D0_{19}$ and $L1_1$-type ordered films are promising candidates for high density recording media, but in all previous reports such films were fabricated on single crystal substrates using molecular beam epitaxy.

We have successfully fabricated m-$D0_{19}$ type and $L1_1$-type Co–Pt ordered alloy films using ultrahigh vacuum (UHV) sputter film deposition on both MgO(111) single crystal substrates and glass disks.[7,8] Experimental results demonstrated the potential of these Co–Pt ordered films for use in data storage applications due to their very high K_u comparable to $L1_0$-type $Fe_{50}Pt_{50}$ films, the relatively low fabrication temperature, and good controllability of the grain orientation. However, the saturation magnetization, M_s, of these films is relatively high; the value of M_s was about 1150 emu/cm^3 for m-$D0_{19}$-type $Co_{75}Pt_{25}$ films and about 900 emu/cm^3 for $L1_1$-type $Co_{50}Pt_{50}$ films. It would be very useful if we could reduce the M_s value, maintaining a large K_u, to tune the magnetic properties of dot arrays to be used for media application.

In this study, we replaced some of the Co with Ni or Fe in Co–Pt alloy films, and fabrication of $L1_1$-type Co–(Ni or Fe)–Pt ordered alloy ternary films was studied using UHV sputter deposition. Ni and Fe are typical ferromagnetic elements in transition metals forming the solid solution with Co. We succeeded in fabricating these ordered alloy films. The magnetic and structural properties of these films will be discussed.

II. EXPERIMENTAL PROCEDURE

Films were deposited using an UHV dc and rf magnetron sputtering system (ANELVA, E8001). The substrate tempera-

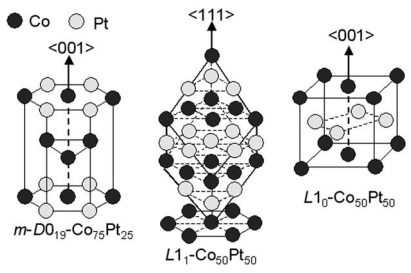

FIG. 1. Crystal structures of the modified $D0_{19}$ (m-$D0_{19}$) and $L1_1$ ordered types for Co–Pt alloy films. The $L1_0$ order structure is also shown for comparison.

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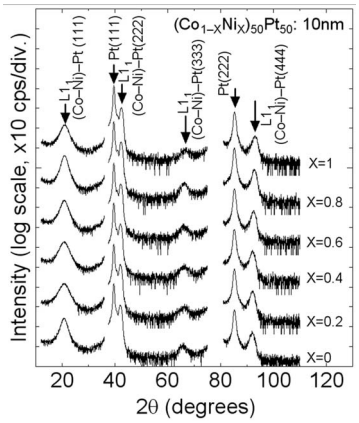

FIG. 2. XRD patterns for $L1_1$-type ordered (Co–Ni)–Pt films with various Ni contents.

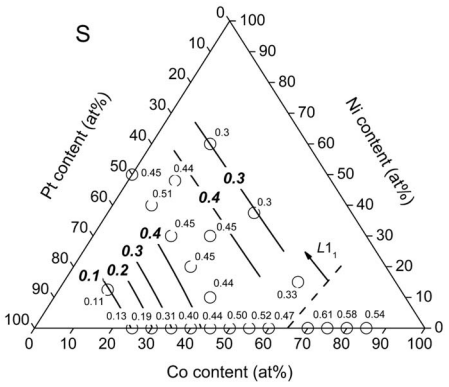

FIG. 3. Values of S as functions of Co, Ni, and Pt contents, with equivalue lines of S. In the figure, the phase boundary between the $L1_1$ and m-$D0_{19}$ ordered structures is also shown as a dotted line.

ture was 360 °C, which is the temperature where the values of S, and K_u nearly saturate.[7,8] The base pressure prior to film deposition was less than 7×10^{-7} Pa. Films were deposited on MgO(111) substrates. Co–Ni–Pt or Co–Fe–Pt films were deposited by the cosputter method, and the film composition was tuned by controlling the deposition rates of Co, Ni, Fe, and Pt. The film thickness was 10 nm. 20 nm thick Pt underlayers were used for the Co–Ni–Pt or Co–Fe–Pt layers. The values of K_u $(=K_{u1}+K_{u2})$ were measured by torque magnetometry and the generalized Sucksmith-Thompson (GST) method,[9] with a maximum applied field of 7 T. The values of K_u obtained by the GST method were in good agreement with those obtained by torque magnetometry.

III. RESULTS AND DISCUSSION

Figure 2 shows the x-ray diffraction (XRD) patterns for $(Co_{1-X}Ni_X)_{50}Pt_{50}$ films with various Ni content, X. All films have a preferred crystal orientation with the close-packed plane parallel to the film plane. Diffraction lines of (Co–Ni)–Pt-$L1_1$(111) planes were observed in all patterns, indicating the formation of a $L1_1$-type ordered structure, although the diffraction width was relatively large. The easy axis distribution, estimated from the rocking curves of the $L1_1$-(222) diffraction line, was about 2°, independent of film composition, due to epitaxial growth of the (Co–Ni)–Pt-$L1_1$(222) planes on the Pt(111) planes. XRD analysis revealed that all films were single crystals. The order parameter, S, calculated using the diffraction intensities for the $L1_1$-(222) and $L1_1$-(111) planes[10] with these stoichiometric compositions was 0.44–0.51, and showed no significant dependence on X.

Figure 3 shows the values of S as functions of Co, Ni, and Pt compositions. Equivalue lines of S are also shown in the figure. The $L1_1$ phase was fabricated over a wide composition range with Co content less than 60 at. %. The phase boundary between the $L1_1$ and m-$D0_{19}$ ordered structures in Co–Pt binary alloy films was at about 65 at. % Co content.[7,8] It is likely that the phase boundary between the $L1_1$ and m-$D0_{19}$ ordered structures in Co–Ni–Pt ternary alloy films is almost along the equivalue line of about 65 at. % Co, as shown in the figure, since the phase boundary between hcp and fcc phases for Co–Ni binary alloys is about 70 at. % Co.[11]

The equivalue lines of S were nearly along the equivalue lines of Pt content. The maximum S values of 0.44–0.51 were obtained for the stoichiometric compositions of $(Co_{1-X}Ni_X)_{50}Pt_{50}$ with various X.

Figure 4 shows the values of M_s as functions of Co, Ni, and Pt compositions, with equivalue lines of M_s. M_s decreased as the Ni content increased, moreover, as the Co content decreased. M_s decreased from 940 to 570 emu/cm^3 as X increased from 0 to 0.6 on the stoichiometric composition line of $(Co_{1-X}Ni_X)_{50}Pt_{50}$.

Figure 5 shows the values of K_u as functions of Co, Ni, and Pt contents, with equivalue lines of K_u. K_u was a maximum along the line of stoichiometric composition of $(Co_{1-X}Ni_X)_{50}Pt_{50}$, which was in good agreement with the contour map of S shown in Fig. 3. K_u decreased as X increased, but maintained a relatively large value of 1.8×10^7 erg/cm^3 even at $X=0.6$, corresponding to a $Co_{20}Ni_{30}Pt_{50}$ composition.

We compared the values of K_u, the K_u/M_s ratio, and S for $L1_1$-type Co–Pt and Co–Ni–Pt alloy films having similar M_s values of 500–600 emu/cm^3, as seen in Table I. The table also shows the values for a $Co_{50}Pt_{50}$ stoichiometric composition for comparison.

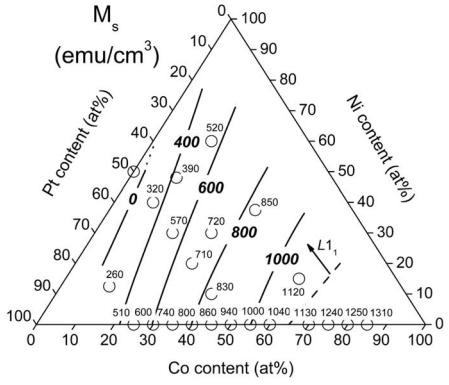

FIG. 4. Values of M_s as functions of Co, Ni, and Pt contents, with equivalue lines of M_s.

TABLE I. Values of K_u, K_u/M_s, and S for $L1_1$-type Co–Pt and Co–Ni–Pt films having M_s of 500–600 emu/cm^3.

Composition (at. %)		M_s	K_u	K_u/M_s	
Pt	Ni	(emu/cm^3)	($\times 10^7$ erg/cm^3)	(kOe)	S
70	0	600	1.2	19.4	0.19
75	0	500	0.7	14.4	0.13
50	30	570	1.8	31.4	0.45
25	60	520	0.8	14.6	0.30
50	0	940	3.7	39.5	0.50

In Co–Pt binary alloy films, a reduction in M_s could be achieved by increasing the Pt content. M_s decreased from 940 to 600 emu/cm^3 and to 500 emu/cm^3 as the Pt content increased from 50 to 70 at. % and to 75 at. %. However the M_s reduction was accompanied by a significant reduction in K_u. K_u decreased from 3.7×10^7 erg/cm^3 (50 at. % Pt) to 1.2×10^7 erg/cm^3 (70 at. % Pt) and 0.7×10^7 erg/cm^3 (75 at. % Pt). The values of K_u/M_s were 19.4 (70 at. % Pt) and 14.4 (75 at. % Pt), which were less than half that of 50 at. % Pt–Co film ($K_u/M_s=39.5$).

The substitution of some Co for Ni was also effective at reducing the M_s value. M_s decreased from 940 to 570 emu/cm^3 as the Ni content increased from 0 ($Co_{50}Pt_{50}$) to $Co_{20}Ni_{30}Pt_{50}$ [corresponding to $X=0.6$ in $(Co_{1-X}Ni_X)_{50}Pt_{50}$]. This substitution of Co to Ni also reduced the K_u value; however, K_u maintained a relatively large value of about 1.8×10^7 erg/cm^3 even at a $Co_{20}Ni_{30}Pt_{50}$ composition. The K_u/M_s ratio at this composition was 31.4, which is about 80% of that of the $Co_{50}Pt_{50}$ binary composition.

Moreover, the value of K_u for the $Co_{15}Ni_{60}Pt_{25}$ composition was 0.7×10^7 erg/cm^3, which was nearly the same as that of the $Co_{25}Pt_{75}$ binary composition, although the Pt content in $Co_{15}Ni_{60}Pt_{25}$ was 1/3 of that in $Co_{25}Pt_{75}$. The substitution of some Co for Ni is an effective way to reduce the Pt content in fabricated films with almost the same magnetic properties. Experimental results indicated that $L1_1$-type Co–Ni–Pt perpendicular films having a large K_u of $(1-2.5)\times10^7$ erg/cm^3 and a relatively low M_s of 400–700 emu/cm^3 were successfully fabricated in the composition range of 10–35 at. % Co, 20–55 at. % Ni, and bal. Pt. K_u should further increase by enhancing the ordering.

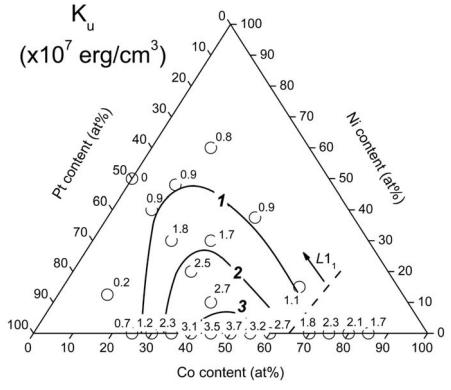

FIG. 5. Values of K_u as functions of Co, Ni, and Pt contents, with equivalue lines of K_u.

We also studied the substitution of some Co for Fe in the stoichiometric compositions of $(Co_{1-Y}Fe_Y)_{50}Pt_{50}$ with various Fe content, Y. $L1_1$-type ordered structures were fabricated in the Y range up to about 0.6, but the S value decreased as Y increased. K_u decreased as Y increased, however, M_s maintained an almost constant value of around 960 emu/cm^3. The values of the K_u/M_s ratio in the $L1_1$-type Co–Fe–Pt films were smaller than those in $L1_1$-type Co–Ni–Pt films.

IV. CONCLUSION

We successfully fabricated $L1_1$-type (Co–Ni)–Pt ordered alloy perpendicular films on MgO(111) single crystal substrates using UHV sputter film deposition. Experimental results demonstrated the potential of these Co–Ni–Pt ordered films for use in data storage applications due to very high K_u comparable to $L1_0$-type $Fe_{50}Pt_{50}$ films, relatively low M_s, the relatively low fabrication temperature, and good controllability of the grain orientation.

ACKNOWLEDGMENTS

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