Magnetic anisotropy of \( L_{11} \)-type \((\text{Co}_{1-x}\text{M}_x)_{50}\text{Pt}_{50} \) (M:Ni, Fe, Cr, Mn) and \( \text{Co}_{50}(\text{Pt}_{1-x}\text{Pd}_x)_{50} \) ordered alloy perpendicular films

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Abstract. We substituted 3d transition elements M (M=Ni, Fe, Cr, and Mn) for some of the Co, or Pd for some of the Pt, in \( L_{11} \)-type \( \text{Co}_{50}\text{Pt}_{50} \) ordered alloy perpendicular films, and studied magnetic and structural properties. Films were fabricated at a substrate temperature of 360°C using ultra-high vacuum (UHV) sputter film deposition. The order parameter \( S \) was almost a constant of about 0.5 when Ni was substituted for some of the Co. The uniaxial magnetic anisotropy \( K_u \) and the saturation magnetization, \( M_s \), decreased as the Ni content increased, however, \( K_u \) maintained a relatively large value of 1.8x10\(^7\) erg/cm\(^3\) (\( M_s=570 \) emu/cm\(^3\)) even for a \( \text{Co}_{20}\text{Ni}_{30}\text{Pt}_{50} \) composition. In the substitutions of Fe for some of the Co, or Pd for some of the Pt, no significant variation in \( M_s \) was observed, however, the rate of decrease of \( K_u \) on increasing the Fe or Pd content was larger than when Ni was substituted. The substitution of Cr or Mn for some Co resulted in significant reductions in \( S \), \( M_s \) and \( K_u \). Experimental results showed the potential of Co-Ni-Pt ordered films for use in data storage applications, due to their very high \( K_u \) potential, relatively low \( M_s \), the relatively low fabrication temperature, and good controllability of the grain orientation.

1. Introduction

\( L_{11} \) type ordered crystal structures having a large uniaxial magnetic anisotropy, \( K_u \), of the order of 10\(^7\) erg/cm\(^3\) have been reported for Co-Pt binary alloys [1-3], in addition to the \( L_{10} \) order structure formed at around \( \text{Co}_{50}\text{Pt}_{50} \) composition. This phase is quasi-stable, and in all previous reports such films were fabricated on single crystal substrates using molecular beam epitaxy. However, we successfully fabricated \( L_{11} \) type \( \text{Co}_{50}\text{Pt}_{50} \) ordered films with the easy axis of magnetization perpendicular to the film plane using ultra-high vacuum (UHV) sputter film deposition on both single crystal substrates and glass disks [4,5]. The experimental results demonstrated the potential of \( L_{11} \) type Co-Pt films for use in data storage applications, due to their very high uniaxial magnetic anisotropy, \( K_u \), of the order of 10\(^7\) erg/cm\(^3\), comparable to \( L_{10} \)-type \( \text{Fe}_{50}\text{Pt}_{50} \) films, the relatively low fabrication temperature of 360 °C, and good controllability of the crystal orientation. Moreover, we succeeded in fabricating \( L_{11} \) type Co-Ni-Pt ordered alloy ternary films [6]. Replacing some of the Co with Ni reduced the saturation magnetization \( M_s \), while maintaining a relatively large \( K_u \), giving an effective way to tune the
magnetic properties of dot arrays to be used for media application. In order to examine further the potential of $L1_1$ type ordered structures, in this study, we substituted 3d transition metals, M, (M=Fe, Cr, and Mn) for some of the Co in Co$_{50}$Pt$_{50}$ alloy films, and fabrication of $L1_1$ type ordered structure was studied using UHV sputter deposition. Moreover we also studied the substitution of Pd for some Pt in $L1_1$ type Co$_{50}$Pt$_{50}$ films. The magnetic and structural properties of these films were studied as a function of the content of the substituting elements, and compared to those for Ni substitution.

2. Experimental procedure
Films were deposited using an UHV DC magnetron sputtering system (ANELVA, E8001). The substrate temperature was 360 °C, which was the temperature where the values of $S$, and $K_u$ were nearly saturated [4,5]. The base pressure prior to film deposition was less than 7x10$^{-7}$ Pa. Films were deposited on MgO(111) substrates. (Co$_{1-M}M$)$_{50}$Pt$_{50}$ films (M=Ni, Fe, Cr, and Mn) or Co$_{50}$(Pt$_{1-X}$Pd$_X$)$_{50}$ films were deposited by the co-sputter method, and the film composition was tuned by controlling the deposition rates of Co, Pt, and M or Pd. The film thickness was 10 nm. 20 nm thick Pt underlayers were used for the Co-M-Pt or Co-Pt-Pd layers. Capping layers of 2 nm thick Pt were deposited on the top of the films. The values of $K_u (=K_{u1}+K_{u2})$ were measured by the GST (Generalized Sucksmith-Thompson) method [7] with a maximum applied field of 7 T. The values of the saturation magnetization, $M_s$, were measured using a vibrating sample magnetometer.

3. Results and discussion
Fig.1 shows the X-ray diffraction (XRD) patterns for Co$_{50}$Pt$_{50}$, (Co$_{0.8}M_{0.2}$)$_{50}$Pt$_{50}$ (M=Ni, Fe, Cr, and Mn), and Co$_{50}$(Pt$_{0.8}$Pd$_{0.2}$)$_{50}$ films. All films had a preferred crystal orientation with the close-packed plane parallel to the film plane. Diffraction lines of $L1_1$-(111) planes were observed in all patterns, indicating the formation of a $L1_1$ type ordered structure at $X=0.2$ in all films, 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 degrees, independent of film composition, due to epitaxial growth of the $L1_1$-(222) planes on the Pt(111) planes. XRD analysis revealed that all films were single crystals.

We calculated the order parameter, $S$, using the diffraction intensities for the $L1_1$-(222) and $L1_1$-(111) planes [8], and show the $S$ values as a function of $X$ in Fig.2. Moreover, Figs.3 and 4 show the values of $M_s$ and $K_u$ for these films, respectively, as a function of $X$. The structural and magnetic properties of the fabricated films are summarized below.

![Figure 1. X-ray diffraction patterns for a Co$_{50}$Pt$_{50}$ binary film, (Co$_{0.8}M_{0.2}$)$_{50}$Pt$_{50}$ ternary films (M=Ni, Fe, Cr, and Mn), and Co$_{50}$(Pt$_{0.8}$Pd$_{0.2}$)$_{50}$ ternary films.](image-url)
3.1 Ni substitution

In the substitution of Ni for some of the Co, the L11 phase was successfully formed over the whole X range from 0 to 1 [6]. S, was almost a constant of about 0.5, independent of X. Ms decreased from 940 emu/cm³ to 570 emu/cm³ as X increased from 0 to 0.6. Further increases of X above 0.6 reduced the Ms value, and Ms at X=1 (Ni50Pt50) was zero. Ku decreased as X increased, but maintained a relatively large value of 1.8x10⁷ erg/cm³ even at X=0.6, corresponding to a Co20Ni30Pt50 composition.

3.2 Fe substitution

The value of S decreased as X increased. No diffraction from the L10-(100) planes was observed in the X range from 0 to 0.6 on tilting the sample at an angle of χ=54.7°. χ is the angle between the normal axis to the film plane and the optical plane. The substitution of Fe for some Co resulted in a slight increase in Ms. However, Ku decreased as X increased, which is in good agreement with the S reduction. The rate of decrease of Ku on increasing X was larger than for the Ni substitution, and Ku at X=0.6 was, relatively small, about 0.5x10⁷ erg/cm³.

3.3 Mn or Cr substitution

The substitution of Cr or Mn for some of the Co resulted in significant reductions in the values of S and Ku. In the Mn substitution, S decreased as X increased, and no diffraction lines from the L11(111) planes were observed at X=0.4. Diffraction from the L110-(100) planes was weakly observed at X=0.4,
by tilting the sample at an angle of $\chi=54.7^o$, indicating the formation of a $L1_0$ phase above about $X=0.4$. $M_s$ decreased as $X$ decreased, however, the $K_u$ reduction was more significant than that of $M_s$, and $K_u$ was about 0.8$x10^7$ erg/cm$^3$ at $X=0.2$. In the substitution of Cr, the rate of decrease of $M_s$ on increasing $X$ was larger than that for the Mn substitution. Moreover, a small amount of Cr of $X=0.05$ resulted in a significant reduction of $K_u$, although the rate of decrease of $K_u$ tended to reduce gradually as $X$ increased. $K_u$ was reduced to less than 1$x10^7$ erg/cm$^3$ at $X=0.2$, however, a relatively clear diffraction line from the $L1_1(111)$ planes was still observed at this value of $X$. These results suggest that the substitution of a small amount of Cr for Co resulted in a phase separation [9]; Cr-poor regions with a $L1_1$ structure and Cr-rich regions were formed in the films, although we have no direct evidence.

### 3.4 Pd substitution

In the substitution of Pd for some of the Pt in $L1_1$ type Co$_{50}$Pt$_{50}$, the value of $S$ decreased gradually as $X$ increased. No diffraction lines from the $L1_1(111)$ planes were observed at $X=1$ (Co$_{50}$Pd$_{50}$ composition). $M_s$ was almost a constant of about 900 emu/cm$^3$ independent of $X$. However, $K_u$ decreased as $X$ increased, which was in good agreement with the $S$ reduction. The spin-orbit interaction strength of Pt is much larger than that of Pd, as theoretically predicted for the $L1_0$-Fe-(Pt, Pd) structure [10], which was another possibility for the enhanced $K_u$ reduction. The rate of decrease of $K_u$ on increasing $X$ was almost the same as that in the substitution of Fe for some Co.

### 4. Conclusion

In the substitutions of Fe for some of the Co and Pd for some of the Pt, no significant variation in $M_s$ was observed, however, the rate of decrease of $K_u$ on increasing Fe or Pd was larger than that for the substitution of Ni. The substitutions of Cr or Mn for some of the Co resulted in significant reductions in $S$, $M_s$, and $K_u$. The phase stability for $L1_1$-$(Co_{1-X}MX)_{50}$Pt$_{50}$ films with various M substitutions was in qualitative agreement with the recent theoretical prediction for $L1_1$-MsPt$_{50}$ fine particles with various M elements (Ni, Co, Fe, Cr and Mn) [11]. Experimental results showed the potential of Co-Ni-Pt ordered films for use in data storage applications, due to their potential for very high $K_u$, relatively low $M_s$, the relatively low fabrication temperature, and good controllability of the grain orientation.

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