Appendix A
Characterization of Magneto-Optical Media

Roger A. Hajjar, Te-ho Wu and M. Mansuripur
Optical Sciences Center
University of Arizona
Tucson, AZ 85721

Amorphous rare earth-transition metal (RE-TM) alloys and compositionally modulated TM TM films (prepared in the laboratories of the ODSC sponsors) are characterized in terms of their magnetic, magneto-optic and galvanomagnetic properties. The loop tracer, vibrating sample magnetometer (VSM), and the Rutherford Backscattering facility (RBS) have been used to characterize and analyze the various properties of these magneto-optical storage media.

The loop tracer consists of a 21 kGauss electromagnet (4" diameter pole piece, 2" gap). The magnet has a rotating stage that allows its field to be applied both perpendicular to and in the plane of the sample. Samples of up to 1" in diameter can be analyzed in a cryogenic dewar cycling temperatures from 80 K to 475 K. The DC differential detection technique is used to measure the magneto-optical Kerr effect at the 633 nm HeNe wavelength. Ellipticity can also be measured with the insertion of a quarter-wave-plate.

The magnetic properties such as coercivity and anisotropy constants at various temperatures are determined form the perpendicular and in-plane measurements of the polar Kerr effect (KE). Galvanomagnetic and transport properties such as the Hall effect (HE), magnetoresistance (MR) and resistivity are measured with two mutually orthogonal pairs of point contacts at the sample surface.

a) Co/Pt Films: The Co/Pt films were prepared by Dr. C-J. Lin of IBM Almaden Research Center. These are multilayered films consisting of alternating ultrathin Co and Pt layers. The films were deposited by e-beam evaporation from Co and Pt sources onto glass substrates. The periodicity and crystallographic structures were obtained by X-ray diffraction analyses and the composition was measured by both XRF and RBS. The total thickness of these films was nominally set to 30 nm where the thickness of the Pt layer was set to about 1.0 nm and the thickness of the Co layer varied from 0.2 nm to 0.4 nm.

All samples show perpendicular magnetic anisotropy and rectangular hysteresis loop in perpendicular magnetic fields. Figures 1 through 4 show the various characteristics of these films versus Co thickness. The remanent Kerr angle and Hall resistivity at room temperature are displayed in Fig. 1. Figure 2 shows the saturation magnetization $M_s$ obtained from the VSM hysteresis loops and $\Delta p/p$ longitudinal obtained from the MR measurement when the field is in the plane of the sample. The value of $\Delta p/p$ is obtained from the peak of the longitudinal MR curve as shown in
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Fig. 5. The linear trend of $\delta_k$, $\varrho_H$, $M_s$ and $\Delta \varrho/\varrho$ (longitudinal peak) correlate with the increase of Co content in these films. From the magnetization data we find that the effective Co moment is around 1750 emu/cc which is considerably enhanced relative to that of bulk cobalt. This enhancement is believed to be due to the stretching of the cobalt lattice which makes it more atomic-like (atomic spin polarization of Co is about twice as large as that of bulk Co). There is little evidence that Pt is polarized as far as we can tell from the $M_s$ data. Evidently, more data points are needed in order to give a quantitative assessment of the Pt polarization.

Figure 3 displays the nucleation coercivity ($H_c$) and anisotropy field ($H_k$) for these films. Both $H_c$ and $H_k$ can be determined from four different measurements, namely: Kerr, Hall, VSM and MR measurements with the applied field being either perpendicular to or in the plane of the sample. The nucleation coercivity can be obtained from KE, HE or VSM hysteresis loops. We can also obtain $H_c$ from the perpendicular MR measurement as illustrated in Figs. 7 and 8. The linear part of the curve in Fig. 8 has a negative slope of $3.1 \times 10^{-8}$ per Oersted, which has its origin in the $s$-$d$ scattering phenomenon as interpreted by Mott. The peaks centered around the coercive field are caused by the scattering of the conduction electrons from the magnetization within the domain walls. These walls cause the resistivity to increase provided that their magnetic moments, while in the plane of the film, are also parallel to the direction of the current. Thus the height of the peaks in Fig. 8 is a measure of the volume fraction covered by the domain walls, while the width of the peaks corresponds to the transition region observed in the vicinity of $H_c$ in the hysteresis loop.

The anisotropy field is determined from the initial part of the KE or HE in-plane measurement (Fig. 6). Also, $H_k$ can be roughly determined from the perpendicular and in-plane VSM measurement by extrapolating the intercept of the in-plane measurement with the saturation part of the hysteresis loop as shown in Fig. 9. $H_k$ is also obtained from the longitudinal MR measurement as shown in Fig. 5. In this measurement, the sample is first saturated along the easy axis. The initial increase of resistivity with the applied field is due to the alignment of magnetization with the field. The maximum of $\Delta \varrho/\varrho$ (longitudinal) is reached at $H = H_k$. Once the magnetization and the field have been aligned, further increases in $H$ cause a linear decrease of $\Delta \varrho/\varrho$ which, as mentioned before, is related to the $s$-$d$ scattering. As shown in Fig. 3, the anisotropy field decreases with increasing cobalt layer thickness. As expected, $H_k$ decreases from a positive value towards negative values, corresponding to an in-plane easy axis of magnetization for thick cobalt layers. A rough extrapolation shows that the crossing point between the perpendicular and in plane anisotropy regimes lies at about 0.7 nm of Co. For ultrathin Co ($< 0.25$ nm), the anisotropy field is reduced mainly due to the island-like formation of the Co layers that become discontinuous.

Figure 4 shows the magnitude of the slope due to $s$-$d$ scattering obtained from the perpendicular MR measurement (see Fig. 8). The data obtained correlate to a certain extent with the total thickness of one period over the thickness of cobalt, $(t_{Co} + t_{Pt})/t_{Co}$. Note that for pure cobalt, where this ratio is equal to 1, the slope obtained is $3 \times 10^{-8}$ per Oersted.
We have also measured the electrical resistivity using the Van der Pauw technique. The resistivity reflects the character of the interfaces in superlattices. For reference, the resistivity of a thick (sputtered) cobalt sample (175 nm thick) was found to be 14 $\mu\Omega\cdot cm$, and those of pure Pd and Pt films (sputtered) were around 17 $\mu\Omega\cdot cm$. The typical room temperature resistivity for a multilayer film is in the range of 30 - 60 $\mu\Omega\cdot cm$. From this behaviour, we can assume that multilayers with abrupt interfaces should have a resistivity intermediate to those of the constituent metals while mixed interfaces will have resistivities as much as a factor of 10 higher. For the samples studied here, the Co/Pt films (30 nm thick) have a typical resistivity of 45 $\mu\Omega\cdot cm$, while similar Co/Pd samples (see next paragraph) have a resistivity of 37 $\mu\Omega\cdot cm$. Adopting the above argument, we attribute the larger resistivity of the Co/Pt films to interfacial mixing between platinum and cobalt layers, and conclude that Co/Pd films have sharper interfaces.

b) Co/Pd Films: A series of Co/Pd multilayer films were fabricated by Dr. Charles Brucker of Kodak Research Laboratories. These are sputtered Co (0.2 nm)/Pd (0.9 nm) films with thicknesses ranging from 5.5 nm to 87.5 nm. Figures 10 - 13 display the thickness-dependence of the magnetic, magneto-optic, and galvanomagnetic properties of these samples at room temperature. The Kerr rotation angle $\Theta_k$ measured from the film side is remarkably enhanced around 11 nm of thickness. This enhancement is due to optical interference between the rays reflected from the film surface and those reflected at the interface between film and substrate; the enhancement is not related to the multilayer structure of the film. Even though the concept of Kerr effect enhancement due to optical interference is well known, we revisit this topic for the sake of completeness.

Consider a magneto-optic film sandwiched between two mediums of indices $n_1$ and $n_3$. The MO layer has two indices of refraction denoted by $n_2^+$ and $n_2^-$, corresponding to left and right circularly polarized light. Knowing that linearly polarized light may be decomposed into left and right circular polarization, we write the Fresnel coefficients as :

\[
R_n^{(z)} = \frac{n_2^{(z)} - n_1}{n_2^{(z)} + n_1}
\]

for reflection off the top surface of the MO layer and :

\[
R_n^{(z)} = \frac{n_2^{(z)} - n_3^{(z)}}{n_2^{(z)} + n_3^{(z)}}
\]

for the reflection off the bottom surface of the MO layer. Assuming multiple reflections within the MO layer, we obtain a general expression of the total reflectivity as follows :
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\[ r(\pm) = \frac{r_1^{(\pm)} + r_2^{(\pm)} \exp (-i\delta(\pm))}{1 + r_1^{(\pm)} r_2^{(\pm)} \exp (-i\delta(\pm))} \]

where \( \delta(\pm) = 4\pi n_\perp^{(\pm)} \times \text{thickness}/\lambda \). Calculation of Kerr rotation angle and ellipticity from the above equation is straightforward7. Figure 14 shows a calculated curve of \( \Theta_k \) and \( \epsilon_k \) versus film thickness. The magneto-optic refractive indices (at \( \lambda = 790 \text{ nm} \)) are obtained from the literature for the film structure \( Co(0.2 \text{nm})/Pd(0.9 \text{nm}) \) with a total thickness of 50 nm.

The electrical resistivity is displayed in Fig. 12 and shows a rapid increase for thicknesses below 16.5 nm. This increase in resistivity can be explained by the change in the film morphology, namely the film growth from an island structure to a continous structure8. The change in the film morphology can also be observed in the magnetic properties such as the anisotropy, coercivity and saturation magnetization where a sharp decrease is observed below 16.5 nm (see Figs. 11 and 13). Note that, as expected, the Hall resistivity in Fig. 10 is independent of the magneto-optical interference effects discussed above and is closely related to the resistivity data. It can be shown9 that \( \rho_h \propto \gamma \rho^2 \), where the coefficient \( \gamma \) is related to the spin-orbit coupling and goes to zero in the absence of spin-orbit coupling. Good agreement is obtained by fitting the data with the theory.

The s-d slope observed in these films is significantly larger than in \( Co/Pt \) films of approximately the same structure as shown in Figs. 15 and 16. This might be attributed to three different phenomena: The d-band structure of cobalt is becoming steeper and closer to the Fermi level (see reference 4), the induced magnetic polarization of \( Pd \), or the extreme proximity of the \( Pd \) Fermi level to the edge of the d-band.

c) TbFeCo Films : A study of the thermomagnetic properties of TbFeCo films is currently underway. These are films of variable \( Tb \) content (ranging from 22.5% to 28%), and were prepared at the IBM Almaden Research Center. The films are deposited onto quartz substrates and consist of a quadrilayer structure of AICr with an MO layer sandwiched between two dielectric SiN layers.

Figure 17 displays the saturation magnetization \( M_s \) versus temperature for these films. Figure 18 shows the \( T_{\text{comp}} \) and \( M_s \) as a function of \( Tb \) content. The sum of the anisotropy energy constants \( K_1 \) and \( K_2 \) at room temperature is displayed in Fig. 19. These parameters are obtained from the in-plane Kerr measurement1. The apparent reduction of \( K_u \) (i.e., \( K_1 + K_2 \)) at the compensation point is not real, but is due to the fact that the maximum field strength in our experiment (\( \approx 21 \text{ KOe} \)) is insufficient to tilt the magnetization away from the perpendicular direction.

Figure 20 shows a typical set of perpendicular and in-plane Kerr effect measurement results for the TbFeCo samples. The bottom frame in Fig. 20 shows the fitting of the normalized in-plane data to the theoretical model (normalization is by the height of the hysteresis loop); it is from this kind of fitting that the anisotropy constants \( K_1 \) and \( K_2 \) are determined.
Plots of the remanent Kerr angle and coercivity, obtained from the hysteresis loops, are shown in Fig. 21. We are currently measuring the temperature-dependence of the various properties of these films in order to determine their anisotropy constants as function of temperature.

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**Fig. 1**

- $\Theta_s$, $\rho_{\text{ned}}$

- $\Theta_s$ (deg)

- $\rho_{\text{ned}}$ (\(\mu\Omega\) cm)

- Co thickness (Å)

**Fig. 2**

- $M_s$, $\Delta \rho/\rho$

- $M_s$ (emu/cm$^3$)

- $\Delta \rho/\rho$

- Co Thickness (Å)

**Fig. 3**

- $H_c$, $H_k$

- $H_c$ (KOe)

- $H_k$ (KOe)

- Co thickness (Å)

**Fig. 4**

- $\Delta \rho/\rho$, $\rho$

- $\Delta \rho/\rho$

- $\rho$ (\(\mu\Omega\) cm)

- Co thickness (Å)
Fig. 5

Fig. 6
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Fig. 10

Fig. 11

Fig. 12

Fig. 13

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OF POOR QUALITY
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Fig. 14

KERR ANGLE AND ELLIPTICITY in deg

FILM THICKNESS in Å

CONCLUSIONS OF POOR QUALITY
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Co(2Å)/Pt(10Å) x 25 (300Å)

Fig. 15

H (KOe)

Δρ/ρ x 1E-3

Co(2Å)/Pd(9Å) x 30 (330Å)

Fig. 16

H (KOe)

Δρ/ρ x 1E-3
Ms Vs Temperature

Fig. 17
$T_{\text{Comp}} \text{ and } M_s \text{ vs } T_b \text{ at. } \%$

- $T_{\text{Comp}}$
- $M_s \text{ (AT RT)}$

Fig. 18
$K_1$ and $K_u$ vs Tb at. %

Fig. 19
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Experimental and theoretical data

Fig. 20

*experimental
-theoretical
\[ \Theta_k \] and \( H_c \) vs \( T_b \) at. %

Fig. 21