

Measurements of the anomalous magnetoresistance effect in Co/Pt and Co/Pd multilayer films for magneto-optical data storage applications

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The anomalous magnetoresistance effect in compositionally modulated TM/TM films (Co/Pt and Co/Pd) has been investigated. Results of measurements on samples at room temperature as a function of the strength of the applied magnetic field are reported. For each sample three different configurations are investigated in which the direction of the applied field is (i) perpendicular to the plane of the film, (ii) in the plane of the film and parallel to the direction of the electric current, (iii) in the plane of the film and perpendicular to the direction of the current. During these measurements the extraordinary Hall effect and the magneto-optical Kerr effect have also been monitored. This additional information, together with the magnetization measurement results obtained from a vibrating sample magnetometer, are used to analyze the data and to explain some of their interesting features.

I. INTRODUCTION

Galvanomagnetic phenomena have been known for many years¹⁻⁵ and have found practical applications in advanced computer storage technology and semiconductor Hall-effect sensors.⁶ They also provide a simple route to measuring some of the electrical, thermal, and magnetic properties of solids. In this paper we restrict attention to the changes induced by an applied magnetic field in the electrical resistivity of thin compositionally modulated TM/TM films (Co/Pt and Co/Pd). This class of material provides suitable recording media for magneto-optical data storage systems.⁷ Magnetoresistance data, obtained at room temperature with the applied magnetic field both parallel and perpendicular to the direction of the electric current, provide a wealth of information about the magnetic properties of these materials. We will present results of these measurements and discuss their various implications for the magnetic structure of the media.

II. EXPERIMENTAL SETUP

In the experiments reported here, the magnetoresistance (MR), Hall effect, and the magneto-optical Kerr effect for each sample were measured simultaneously at room temperature. Resistivity measurement was done using the Van der Pauw technique.⁸ The measurements are performed in an electromagnet with maximum field capability of 20 kOe. The magnet has a rotating stage that allows its field to be applied both perpendicular to and in the plane of the sample. The three different geometries for measurements of the magnetoresistive and Hall effects are illustrated in Fig. 1. Figure 1(a) shows the perpendicular geometry, where the field is normal to the plane of the sample and the current flows between point contacts 1 and 2. The Hall effect is measured between terminals 3 and 4. In the longitudinal geometry shown in Fig. 1(b) the magnetic field is in the plane of the sample and parallel to the direction of the current, which flows between terminals 1

and 2. The transverse geometry, shown in Fig. 1(c), is similar to the longitudinal case, with the exception that the current terminals are now terminals 3 and 4. The magneto-optical Kerr effect is measured using a normally incident beam from a HeNe laser and a differential detection module that monitors the polarization state of the reflected light.⁹

The resolution of the resistance measurements is about $100 \mu\Omega$, while the power dissipation in the sample is kept below 1 mW. The $1 \times 1.5\text{-cm}^2$ samples are connected to the signal processing electronics via two mutually orthogonal pairs of point contacts.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Measurements have been performed on several samples. We discuss the results pertaining to Co/Pt and Co/Pd in two separate subsections, presenting the data for a typical sample in each case.

A. Co/Pt

The sample is an evaporated Co(5 Å)/Pt(10 Å) superlattice with 20 bilayers. Results of VSM measurements on this sample at room temperature, with the applied magnetic field both perpendicular to and in the plane of the film are shown in Fig. 2(a). The sample has saturation magnetization $M_s = 410 \text{ emu/cm}^3$ and coercive field $H_c = 1.3 \text{ kOe}$. The reversal process takes place by a rapid nucleation of domains at $H = H_c$, resulting in the steep part of the hysteresis loop, followed by a rather slow growth of these domains that requires an additional field of 1 kOe for the completion of the reversal process. The extrapolation of the in-plane VSM curve intersects the perpendicular curve at $H \approx 12.5 \text{ kOe}$, which is the anisotropy field $H_k = 2K_u/M_s$. The uniaxial anisotropy energy constant for the sample is thus obtained as $K_u \approx 2.5 \times 10^6 \text{ erg/cm}^3$.

Starting from a demagnetized state and applying the magnetic field perpendicular to the plane of the sample, we

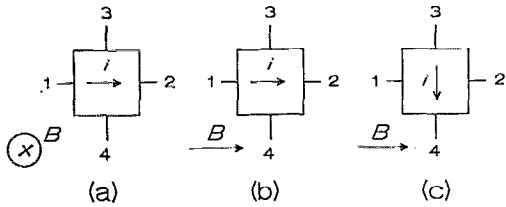


FIG. 1. Schematic diagram of the magnetoresistance and Hall-effect measurements: (a) perpendicular geometry, (b) longitudinal geometry, (c) transverse geometry.

obtained the Hall loop shown in Fig. 2(b). The Hall resistivity in the saturated state is $\rho_{\text{Hall}} = 1.2 \mu\Omega \text{ cm}$. The result of measurement of the Hall effect when the sample is initially saturated in the perpendicular direction and the applied field is in the plane of the sample is shown in Fig. 2(c). The initial slow decrease in the Hall voltage is due to the rotation of M towards the field. Following this initial phase, the rapid drop in the Hall voltage indicates the breakup of the magnetization into oppositely magnetized domains. This breakup into domains is not predicted by the coherent rotation theory of Stoner and Wohlfarth,¹⁰ but occurs in practice probably due to the existence of inhomogeneities in the sample such as regions with slightly different axes of anisotropy. The small hysteresis loop in

Fig. 2(c) that is obtained by scanning the field, is repeatable and is probably due to the motion of domain walls in the demagnetized state. Alternatively, this hysteretic behavior might be related to the small deviations of the local easy axes across the sample. The value of H_k estimated from the curvature of the initial part of this curve (near the top) is about 11 kOe, which is somewhat less than the value obtained for H_k from VSM measurements.

Figure 2(d) is a plot of $\Delta\rho/\rho$ vs H , where H is the magnitude of the applied field perpendicular to the plane of the film and $\rho = 58 \mu\Omega \text{ cm}$ is the initial resistivity at $H = 0$. The linear part of the curve, with a negative slope of 3.1×10^{-8} per Oersted has its origin in the s - d scattering phenomenon as interpreted by Mott.² 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. 2(d) 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 loops.

Figure 2(e) shows the measured values of $\Delta\rho/\rho$ vs H in the longitudinal case. At first, the sample is saturated

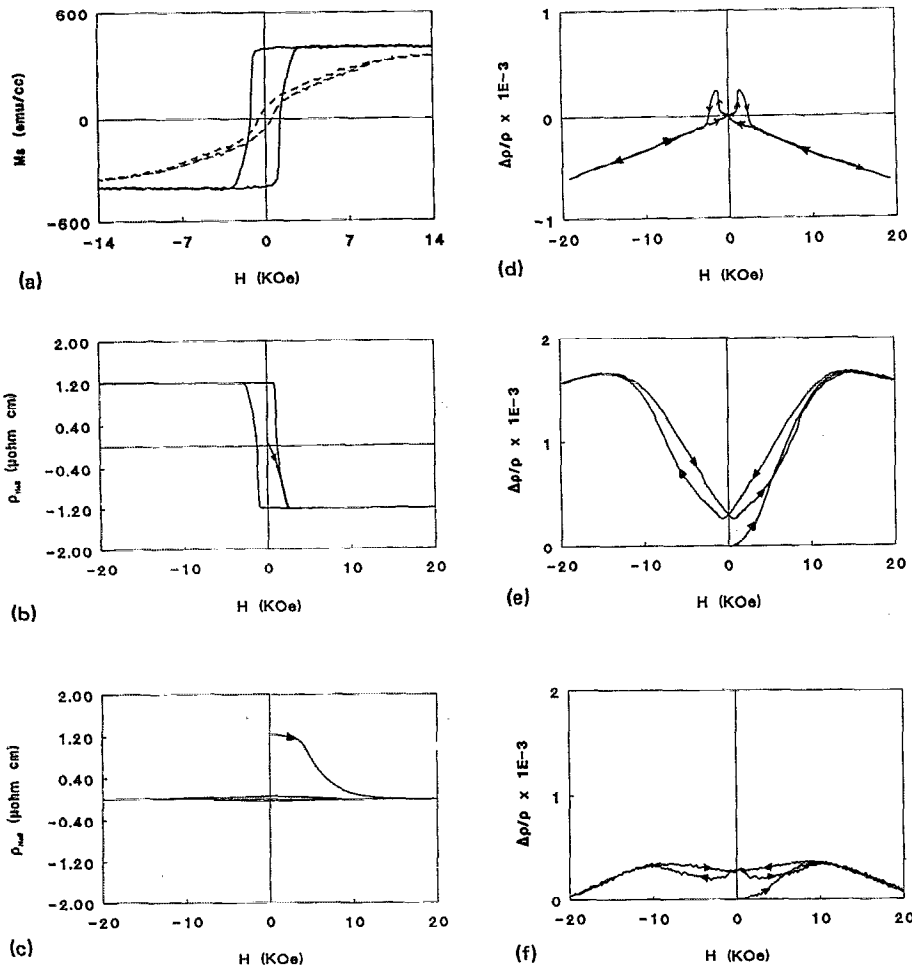


FIG. 2. Measurement of Co(5 Å)/Pt(10 Å) 300 Å thick. (a) VSM perpendicular (-) and in-plane (--); (b) Hall loop, (c) in-plane Hall curve; (d) perpendicular MR; (e) longitudinal MR; (f) transverse MR.

along the easy axis. The initial increase of the resistance with H is due mainly to the alignment of the magnetization vector M with the current. As expected, the maximum is reached at $H = H_k \approx 12.5$ kOe. Once the magnetization and the field have been aligned, further increases in H cause a linear decrease of $\Delta\rho/\rho$ that, as before, is related to s - d scattering.

It is seen in Fig. 2(e) that when H is brought back to zero the resistance is somewhat larger than its initial value. This is to be expected, simply because the sample is no longer saturated. The difference in $\Delta\rho/\rho$ between the initial (saturated) state and the demagnetized state is about 3.0×10^{-4} , which is somewhat larger than the height of the peaks in Fig. 2(d). Thus the two demagnetized states, one created by a perpendicular field and the other by an in-plane field, have slightly different structures.

In Fig. 2(f) we show the measured values of $\Delta\rho/\rho$ vs H in the transverse case. Starting from the state of magnetization saturated along the easy axis, the resistance is seen to increase at first, peaking at $H \approx 10$ kOe before it begins to decrease. As in the previous case, the linear decrease with a slope of 3.1×10^{-8} per Oersted at $H > H_k$ is due to the s - d scattering effect. The initial increase and then decrease of $\Delta\rho/\rho$ is partly due to the breakup of the saturated state into various domains. There is also the possibility that the geometry of the probes inadvertently permits a fraction of the current to flow along the direction of the field, thus enabling the current to sense the magnetization M as it moves into the plane.

B. Co/Pd

Another set of measurements was performed on a superlattice sample made of 77 bilayers of Co(2 Å)/Pd(9 Å). Qualitatively this sample's characteristics are similar to the Co/Pt sample discussed above. The absolute values of parameters, however, are significantly different. The film is sputtered on a glass substrate and has a perpendicular easy axis. The saturation magnetization $M_s = 300$ emu/cm³ and the anisotropy field extracted from the VSM data is $H_k = 16$ kOe. The zero-field resistivity is $\rho = 77$ $\mu\Omega$ cm and the Hall resistivity is 0.075 $\mu\Omega$ cm. Figure 3(a) shows the perpendicular MR for this sample. The longitudinal MR curve is shown in Fig. 3(b) and peaks at 15.5 kOe. Both MR curves show the s - d effect with a negative slope of 25×10^{-8} per Oersted which is substantially larger than the corresponding slope observed for the Co/Pt sample. The large magnitude of the s - d effect in Co/Pd might be indicative of the polarization of palladium layers at interfaces with cobalt. Details of this dependence and the correlation of the slope to the induced magnetization of Pd is not understood at present.

IV. CONCLUSION

We have reported the results of VSM, Hall-effect, and magnetoresistance measurements on superlattice films. Magnetoresistance measurements contribute to our understanding of magneto-optical recording media. In addition to the coercivity and anisotropy field measurement, mag-

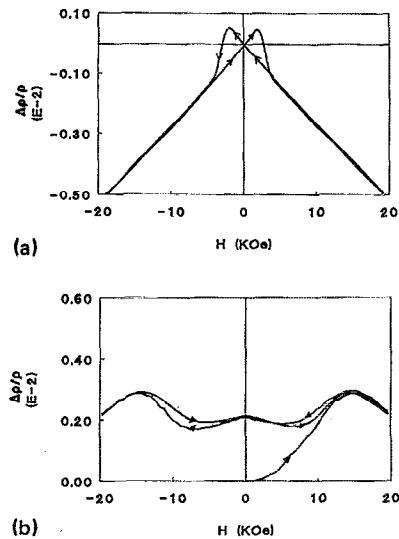


FIG. 3. MR measurement on a Co(2 Å)/Pd(9 Å) 847 Å thick: (a) perpendicular case; (b) longitudinal case.

netoresistance determines the magnitude of the s - d electron transitions in superlattices. Among the intriguing possibilities suggested by the different magnetoresistance slopes between Co/Pt and Co/Pd, we mention a significant contribution by Pd polarization.

ACKNOWLEDGMENTS

The authors are grateful to Dr. C. J. Lin of IBM's Almaden Research Center and Dr. C. Brucker of Kodak Research Laboratories for providing the superlattice samples. This work has been supported by the Optical Data Storage Center at the University of Arizona. One of us (R.A.H.) would also like to acknowledge the support of an IBM fellowship.

- ¹W. Thomson, Proc. R. Soc. London **8**, 546 (1857).
- ²N. F. Mott, Proc. R. Soc. London **156**, 368 (1936).
- ³T. Kasuya, Progr. Theoret. Phys. (Kyoto) **16**, 58 (1956).
- ⁴J. P. Jan, in "Galvanomagnetic and Thermomagnetic effects in metals," *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic, New York, 1957), Vol. 5, pp. 1-96.
- ⁵T. R. McGuire and R. I. Potter, IEEE Trans. Magn. **MAG-11**, 1018 (1975).
- ⁶D. A. Thompson, L. T. Romankiw, and A. F. Mayadas, IEEE Trans. Magn. **MAG-11**, 1039 (1975).
- ⁷C. J. Lin and H. V. Do, IEEE Trans. Magn. **MAG-26**, 1700 (1990).
- ⁸L. J. van der Pauw, Philips Tech. Rev. **20**, 220 (1958).
- ⁹P. Wolniansky, S. Chase, R. Rosenvold, M. Ruane, and M. Mansuripur, J. Appl. Phys. **60**, 346 (1986).
- ¹⁰E. C. Stoner and E. P. Wohlfarth, Philos. Trans. R. Soc. London, Ser. A **240**, 599 (1948).