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Magnetotransport and magnetic properties of molecular-beam epitaxy $L1_0$ FePt thin films

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The magnetotransport and magnetic properties of chemically ordered (001) $L1_0$ FePt epitaxial thin films with small scale perpendicularly magnetized stripe domains have been investigated. Film growth conditions are used to systematically vary the degree of chemical order, the magnetic anisotropy, and magnetic domain sizes. The longitudinal and transverse (Hall) resistivities are correlated with both film chemical order and magnetic properties. The low-field magnetoresistance shows evidence of domain effects. In the highest anisotropy and most chemically ordered film studied, this low field magnetoresistance is consistent with an intrinsic domain wall scattering contribution to the resistivity.

I. INTRODUCTION

The effect of domain structure on the electronic transport properties of magnetic thin films has recently been intensively studied. A focus has been to develop model thin film structures to study domain wall (DW) scattering effects[1–6] and, particularly, to test recent theoretical ideas.[7,8] In our research on epitaxial bcc Fe and hcp Co, lithography was used to control stripe domain configurations and the orientation of DWs with respect to current flow in microstructures.[1–3] The contribution of DWs to resistivity was found to be small compared to conventional anisotropic transport effects, and to be either positive (increase the sample resistivity) or negative. Higher anisotropy uniaxial thin film materials offer the possibility of both larger DW scattering effects and further control of magnetic domain configurations in restricted geometries. Here, we present results on chemically ordered (001) $L1_0$ FePt epitaxial thin films with perpendicularly magnetized stripe domains. These films have among the highest known magnetic anisotropy energy ($K \sim 10^8$ erg/cm^3) of any ferromagnetic material.[9]

II. EXPERIMENT

Epitaxial (001)-oriented $L1_0$ $Fe_{1-x}Pt_x$ ($x \sim 0.5$) thin films (100 nm thick with thin Pt seed and cap layers) were grown by molecular-beam epitaxy (MBE) in ultrahigh vacuum on (001) MgO substrates as described in Ref. 9. The substrate temperature was varied between 150 and 500 °C. X-ray diffraction analysis was used to determine the degree of chemical order ($S/S_{\max}$) and film composition was determined by Rutherford backscattering (RBS) analysis.[9]

The room-temperature magnetic properties have been measured using both torque and vibrating sample magnetometry. Domain structure was studied in zero applied field using a magnetic force microscope (MFM) with a vertically magnetized CoCr-coated Si tip. Prior to imaging, the films were demagnetized with a field applied perpendicular to the film plane. The light and dark contrast in images is associated with magnetization parallel or antiparallel to the film normal. The magnetic tip did not noticably perturb the film domain structure.

Magnetotransport measurements were performed in a variable temperature high-field cryostat with *in situ* (low temperature) sample rotation capabilities. The films were patterned using optical lithography and ion milling to produce 20 μm linewidth wires with contacts for measurement of both longitudinal and transverse (Hall) resistivities. The applied field was oriented perpendicular to the film plane (and current) as well as in the film plane and parallel to the current, denoted the longitudinal field geometry. A four-probe ac (~10 Hz) resistance bridge and low bias currents (100–200 μA) were employed.

III. RESULTS

Table I summarizes the properties of the films studied. With increasing substrate temperature there is a greater degree of chemical order and a higher uniaxial anisotropy constant. Torque measurements on samples 1079 and 1080, (and to a lesser extent on 1075) also indicate higher order components to the anisotropy, and that these films may be inhomogeneously ordered.[10]

Figure 1 shows MFM images at room temperature of films 1075 and 1080. The average domain size is larger in the higher anisotropy film (1075, ~200 nm). Domains form due to a competition between magnetic energies; the exchange, dipolar (magnetostatic) and anisotropy energies. An important parameter is the ratio of magnetocrystalline to magnetostatic energy density, $Q = K/2\pi M^2$. For film 1075, we estimate $Q = 10$. For such a large Q, stripe domains which intersect the surface with M perpendicular to the film surface are energetically favored.[11] Qualitatively larger anisotropy leads to a greater DW energy and hence larger domains, as observed.

Figure 2(a) shows MR measurements with the field oriented perpendicular (solid lines) to the film plane at 280 and

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TABLE I. Structural, magnetic, and transport characteristics of the films studied. δ is an estimate of the domain wall width $[\pi\sqrt{(A/K_u)}$, with $A=10^{-6}$ erg/cm], d is the average domain size, ρ is resistivity, and RRR is the residual resistivity ratio. Other symbols are as defined in the text.

Sample	T_g (°C)	x	S/S_{max}	M_s (emu/cc)	K_U (10^7 erg/cc)	δ (nm)	d (nm)	ρ ($\mu\Omega$ cm) (1.7 K)	RRR	Domain MR (1.7 K)	$(\rho_{xy}/\rho_{xx})^2$ (1.7 K)
1075	500	0.49	0.80	834	4.30	4.4	210	7.2	3.0	2.8×10^{-3}	9.1×10^{-5}
1079	250	0.56	0.63	745	~0.31	18	165	18.5	2.2	1.2×10^{-3}	3.1×10^{-4}
1080	150	0.51	0.47	837	~0.28	19	90	26.6	1.8	1.1×10^{-3}	1.1×10^{-3}

1.7 K. In the low-field region, hysteresis is observed in the MR which correlates well with the magnetic hysteresis measurements. At low temperature, the high-field MR is positive and quadratic with field. This we associate with the ordinary (Lorentz) MR. At 280 K, the high-field MR is negative and decreases nearly linearly out to the largest fields that we are able to apply (10 T). Such a negative MR is typically associated with the magnetic field suppression of spin-disorder scattering.[12,13]

Measurements in the longitudinal field geometry (with the field at 5° to the film plane) are indicated by dashed lines in Fig. 2. Resistivity anisotropy is noticeable at both high and low temperatures. At low temperature (1.7 K), differences are observed particularly when magnetic domains are present, between -8 and 8 T. At 280 K, the resistivity in the longitudinal geometry is generally larger than that in the perpendicular geometry. This is again associated with magnetic domain structure, which we discuss below.

Figure 2(b) shows the transverse or Hall resistivity as a function of field at 1.7 K. These characteristics are again hysteretic, reflecting the magnetic hysteresis. As commonly observed in ferromagnetic materials there is an ordinary linear high-field component and an extraordinary component proportional to the sample magnetization.[12] The extraordinary component is associated with the spin-orbit interaction, which leads to both asymmetric scattering (skew scattering) and a side-jump mechanism for the Hall effect. This latter contribution is predicted to scale as ρ_{xx}^2.[14] The inset of Fig. 2(b) shows a log-log plot of ρ_{xy} vs ρ_{xx}. We observe $\rho_{xy} \sim \rho_{xx}^2$, consistent with the side-jump mechanism.

Figure 3 shows similar magnetotransport measurements on a lower anisotropy film (1080) with greater chemical disorder. At the lowest temperature, the resistivity is nearly field independent, and indicates a suppression of the Lorentz MR with increasing film disorder. At higher temperature, a negative linear high-field MR is observed. Figure 3(b) shows that the extraordinary Hall angle is greatly enhanced with respect to that of 1075, consistent with the side jump mechanism $(\rho_{xy}/\rho_{xx} \sim \rho_{xx})$.

IV. DISCUSSION

These magnetotransport results illustrate that domain structure has a significant effect on film resistivity in such materials. For instance, in film 1075, the resistivity is enhanced by 0.2%–0.3% at low fields and temperatures due to the presence of magnetic domains. We denote this enhancement the domain MR. At 280 K, a smaller enhancement in the resistivity is observed near zero field in the perpendicular MR. The larger resistivity in the longitudinal geometry may be associated with the orientation of the domains. MFM imaging shows that after longitudinal measurements at 280 K,

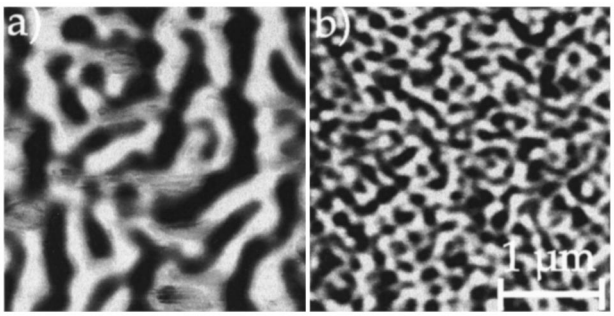

FIG. 1. MFM images in zero applied field of $Fe_{1-x}Pt_x$ (a) 1075, a well-ordered, high anisotropy film and (b) 1080, lower growth temperature and anisotropy.

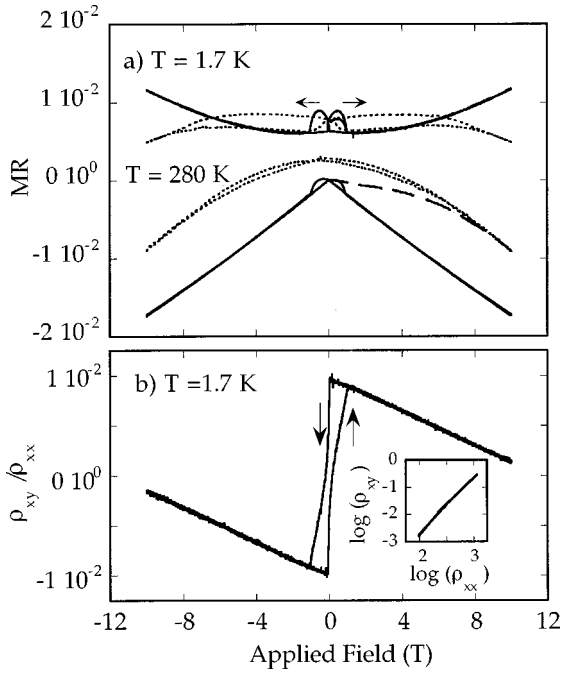

FIG. 2. (a) MR data of a 20 μm linewidth wire of FePt 1075 at 1.7 and 280 K. The solid line is with the applied field oriented perpendicular to the film plane and the dashed line is for the field oriented 5° from the film plane and parallel to the current. The field is purposely misaligned from the plane by this angle so that the sample is in a well-defined (single domain) magnetic state at high field. (b) The Hall angle, $\rho_{xy}/\rho_{xx'}$ vs perpendicularly applied field at 1.7 K. The inset in (b) shows a log-log plot ρ_{xy} vs ρ_{xx}.

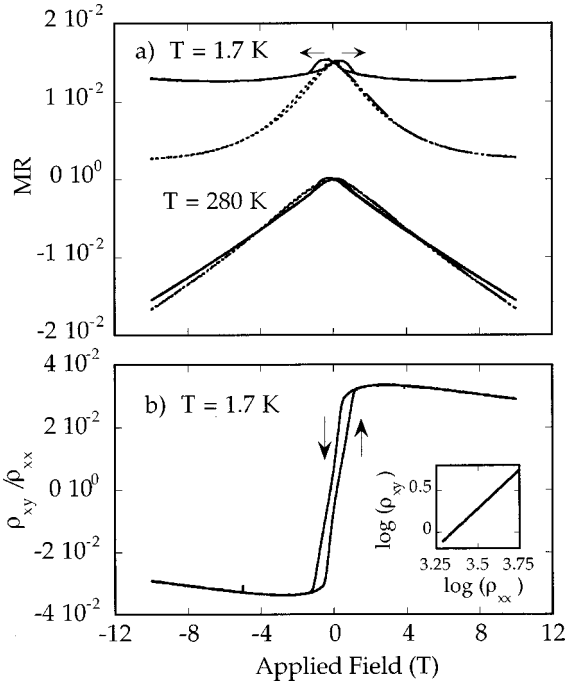

FIG. 3. (a) MR data of a 20-μm-linewidth wire of FePt 1080 at 1.7 and 280 K in a perpendicular applied field. (b) The Hall angle vs perpendicularly applied field at 1.7 K. The inset shows a log-log plot of ρ_{xy} vs ρ_{xx}.

DWs tend to align perpendicular to the current, instead of in the maze like pattern seen in Fig. 1. Low-field enhancements in resistivity, somewhat smaller in magnitude (0.1%) are also observed in film 1080.

An important question is the physical mechanism of this resistivity enhancement—whether it is due to an *intrinsic* DW scattering contribution[7,8] to the resistivity or ''domain'' effects. A number of domain effects have been discussed in the literature.[15] Ferromagnetic resistivity anisotropy is a mechanism by which a multidomain sample may have a higher resistivity than that of a single domain sample.[3] Berger has also discussed a domain mechanism which can enhance resistivity based on the Hall effect.[15] The Hall effect leads to current deflection near a domain wall, due to the angle between the electric field and current in domains. Since the Hall angle changes sign in alternating magnetization domains, current will zigzag through the sample and the resistivity is predicted to be increased of order $(\rho_{xy}/\rho_{xx})^2$.

In the high anisotropy film (1075), these domain effects appear to be of insufficient magnitude to explain the observed increase in resistivity. For the Hall effect mechanism, the observed increase of 0.3% is more than one order of magnitude larger than $(\rho_{xy}/\rho_{xx})^2 \sim 0.01\%$ at 1.7 K. Also, while the Hall angle decreases as the temperature is reduced, the domain MR increases (Fig. 4). Further, the ferromagnetic resistivity anisotropy is small (Fig. 2) and due to the large

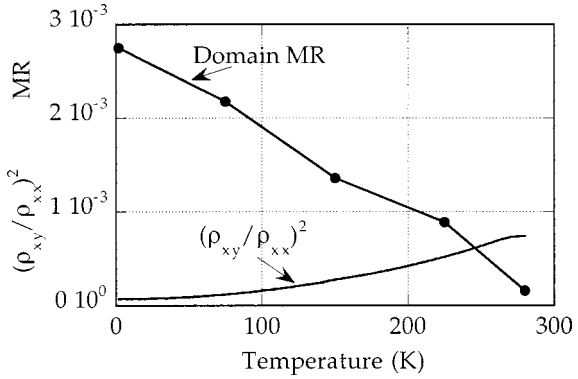

FIG. 4. Domain MR and $(\rho_{xy}/\rho_{xx})^2$ vs temperature for sample 1075.

uniaxial anisotropy domain magnetization is mainly perpendicular to the film plane and hence current. Film 1080 has a lower anisotropy, a smaller domain size and hence a larger density of DWs, yet the magnitude of the domain MR is reduced, $\sim$0.1%. In this film, $(\rho_{xy}/\rho_{xx})^2$ is also same order of magnitude and the Hall mechanism may be relevant.

Hence, in the high anisotropy film, an intrinsic spin-dependent DW scattering contribution to the resistivity[7,8] may be at the origin low-field enhancement of the resistivity. Since such DW scattering effects are predicted to depend strongly on DW width, it would be interesting to extend such studies to even more ordered films and lithographic defined structures.

ACKNOWLEDGMENTS

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