Large magnetic Hall effect in ferromagnetic \( \text{Fe}_x \text{Pt}_{100-x} \) thin films

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We have observed a very large extraordinary Hall effect (EHE) in a series of Fe–Pt thin films with various Fe contents. The origin of this remarkable EHE is the large spin–orbit interaction in the Fe–Pt alloys. At certain Fe content, the Hall resistivity can be saturated with a magnetic field less than 2 kG. The large EHE persists to room temperature with little change in magnitude. The EHE, which to our knowledge is the largest among magnetic transition metals, may find potential applications in magnetic sensors and nonvolatile magnetic random access memories. We will present structural analysis of the Fe–Pt films. © 1996 \textit{American Institute of Physics.}

The study of magnetotransport in magnetic solids has received an increasing amount of attention recently.\textsuperscript{1} The primary driving force behind this study is the potential applications of various novel magnetic solids in information storage devices and magnetic sensors.\textsuperscript{2} Most of the research in this area has focused so far on the magnetoresistance aspect, with relatively little attention being paid to the magnetic Hall effect, often called the extraordinary Hall effect (EHE). The EHE arises from the spin–orbit interaction and it can be substantially larger than the ordinary Hall effect.\textsuperscript{2} Currently, a large class of magnetic sensors is the semiconductor Hall sensor which offers good field sensitivity and linearity. However, due to a low carrier concentration, the internal resistance of a semiconductor Hall sensor is large and the frequency response narrow. Metallic solids, though having a high conductivity and a broad frequency response, are not suitable for Hall sensors because of the small Hall coefficient resulting from the inherently high carrier concentration. However, it has been suggested in the past that one may take advantage of the EHE of some magnetic solids and apply it to data storage devices or other types of magnetic sensors.\textsuperscript{3} In reality, a large EHE generally occurs in rare-earth based magnetic systems where the spin-orbit interaction is strong,\textsuperscript{2} but the rare-earth systems tend to have low magnetic transition temperatures \( T_c \) and are rather susceptible to corrosion.

In this work, we report on a very large EHE uncovered in a transition-metal system of \( \text{Fe}_x \text{Pt}_{100-x} \) thin films. The EHE coefficients are roughly three orders of magnitude larger than a typical ordinary Hall coefficient of a metal. The EHE saturates at a couple of kG and remains large at room temperature. We attribute the large EHE to the strong spin–orbit interaction existing in the Fe–Pt alloys.

The Fe–Pt thin films used in this study were deposited on silicon (111) substrates by using the magnetron-sputtering technique. We used the co-sputtering method to obtain samples with varying composition. Two of the collimated cluster guns were loaded, respectively, with an Fe sample with varying composition. Two of the collimated cluster guns were loaded, respectively, with an Fe target. The composition of each sample was controlled by varying the sputtering rates of the two targets. Before each deposition the background vacuum was better than 7\( \times \)10\(^{-8} \) Torr. The Ar sputtering gas pressure was kept at 4.0 mTorr. All samples were deposited at an ambient substrate temperature. The film thickness was about 2500 Å. The structure of each sample was checked using an x-ray powder diffractometer. The standard photolithography and wet etching were used to pattern samples for transport measurement. The magnetic properties were measured in a superconducting quantum interference device magnetometer.

The equilibrium phase diagram of the Fe–Pt system consists of two face-centered-cubic (fcc) (FePt\(_3\) and Fe\(_3\)Pt), one tetragonal superstructures (FePt) and a continuous solid solution in the \( \alpha \)-Fe-rich side.\textsuperscript{4,5} We have made a series of samples with Fe content ranging from 0 to 50 at. %. The high quenching rate inherent in sputtering allows the formation of metastable Fe–Pt solid solutions. Figure 1 shows the \( \theta–2\theta \) x-ray diffraction patterns of the \( \text{Fe}_x \text{Pt}_{100-x} \) thin films used in our study. Only the (111) and (222) peaks of the fcc structure are present, indicating textured growth. The details of the (111) and (222) peaks are present for various Fe contents.

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  \caption{X-ray diffraction patterns of the \( \text{Fe}_x \text{Pt}_{100-x} \) alloys. Only (111) and (222) peaks of the fcc structure are present, indicating textured growth. The details of the (111) and (222) peaks are shown for various samples.}
\end{figure}
are present, indicating a high degree of (111) textured growth of the thin films. No secondary phases were found in the x-ray patterns. The position of the (111) and the (222) peaks shifts toward high angles as the Fe content is increased (see Fig. 1). The obtained lattice constants \( a \) are shown in Fig. 2. Note that the value of \( a \) decreases monotonically with the Fe content.

All of the samples that we studied are ferromagnetic. For samples with an Fe content larger than 20 at.\%, \( T_c \) is above 300 K. We have also observed giant Fe moments largely exceeding those in pure Fe. The enhanced moment is caused by the narrowing of Fe \( d \) band and the polarization of the Pt \( d \) states. Detailed study of this phenomenon is underway and will be presented elsewhere.

In the following, we will focus on the EHE observed in the Fe–Pt system. In general the Hall effect is sensitive to the magnetic state of the material. This is clearly revealed in Fig. 3, where we show the Hall resistivity \( \rho_{xy} \) as a function of magnetic field \( H \) for a representative Fe\(_{30}\)Pt\(_{70}\) sample measured at 4.2, 77, and 285 K. The value of \( \rho_{xy} \) is defined according to

\[
\rho_{xy} = \frac{V_y}{I_x} t = \frac{E_y}{I_x} t,
\]

where \( E_y, V_y, j_x, I_x \) are electric field, voltage, current density, and current, respectively, \( t \) is the thickness of the Hall bar. The value of \( \rho_{xy} \) consists of two components, i.e.,

\[
\rho_{xy} = \rho_{0} [H + 4\pi M(1 - D)] + R_s A\pi M,
\]

where the first term is the ordinary Hall effect (\( D \) is the demagnetization factor), and the second term is the EHE which is proportional to the magnetization \( M \). The dependence of \( \rho_{xy} \) shown in Fig. 3 follows the magnetic hysteresis curve closely. The large initial increase in \( \rho_{xy} \) with \( H \) is due to the EHE. Once \( M \) is saturated, so is \( \rho_{xy} \). Above the saturation \( H, \rho_{xy} \) is nearly independent of \( H \) at \( T = 4.2 \) and 77 K. The normal Hall effect is too small to be visible in Fig. 3. At \( T = 285 \) K, the increase of \( \rho_{xy} \) with \( H \) in the high field region is not due to the normal Hall effect, but rather due to the fact that \( M \) remains unsaturated up to 6 T.

In Fig. 4, we plot the EHE term at saturation (i.e., \( R_s A\pi M_s \)) as a function of Fe content for the Fe\(_{100-x}\)Pt\(_x\) alloys. The values of \( R_s A\pi M_s \) were obtained by extrapolating the \( \rho_{xy}(H) \) curve from high field to \( H = 0 \). At \( T = 4.2 \) and 77 K, the quantity \( R_s A\pi M_s \) peaks at the Fe content of 30%. The initial rise of \( R_s A\pi M_s \) with Fe content is simply caused by the increasing concentration of magnetic scattering centers. However, as the Fe content is increased the spin–orbit coupling strength, mostly resulting from the heavy Pt atoms, becomes less effective. This eventually causes the EHE.

FIG. 2. Lattice constants of the fcc–Fe\(_{100-x}\)Pt\(_x\) alloys, obtained from the (111) and (222) peaks in Fig. 1.

FIG. 3. Hall resistivity, \( \rho_{xy} \), as a function of magnetic field measured at 4.2, 77, and 285 K for Fe\(_{30}\)Pt\(_{70}\).

FIG. 4. The extraordinary Hall resistivity, \( R_s A\pi M_s \), measured at 4.2, 77, and 285 K for the Fe\(_{100-x}\)Pt\(_x\) alloys. The lines are guides to the eyes.
EHE. The peak of samples are no longer ferromagnetic, thus suppressing the netic at 77 K. However, at rather similar to that at 4.2 K. All samples remain ferromag- small saturation field, which is equal to 4\(p\). To achieve a large Hall slope it is preferred to have a produced. Overall, the EHE remains robust at room temperature whereas the the metal such as Cu, the Hall slope in the Fe–Pt alloys is enhanced by three orders of magnitude.

The large EHE in Fe–Pt could be potentially important for applications, such as magnetic sensors and nonvolatile magnetic random access memories (MRAM). In one version of MRAM each memory cell consists of a small Hall bar with a large EHE and a magnetic perpendicular anisotropy. The hysteresis loop is squarelike when the field is oriented perpendicular to the Hall bar. A local current loop switches the \(M\) to either an up or down direction yielding a Hall voltage with opposite polarity. The Fe–Pt system has both the metallic conductivity and the large EHE. The magnetic perpendicular anisotropy can be achieved by making either sandwich or multilayer structures involving Fe–Pt. The surface or interface magnetic anisotropy may cause the perpendicular anisotropy.

In summary, we have fabricated a series of fcc–Fe\(_{30}\)Pt\(_{70}\) thin films. Due to a large spin–orbit interaction, the Fe–Pt alloys exhibit a very large extraordinary Hall effect which can be saturated with a field of a couple of kG. Optimal magnetic Hall resistivity and Hall slope at room temperature are found in the sample Fe\(_{30}\)Pt\(_{70}\), which is a good candidate for applications.

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FIG. 5. The initial Hall slope, \(d\rho_{xy}/dH\), at 4.2, 77, and 285 K for the Fe\(_{x}\)Pt\(_{100-x}\) alloys. The lines are guides to the eyes.

originating from the spin–orbit interaction, to weaken when the Fe content exceeds 30%, despite an increasingly larger \(M\). The peak value of \(R_4\pi M\), occurring in Fe\(_{30}\)Pt\(_{70}\) is 5.5 \(\mu\Omega\) cm. This is perhaps the largest magnetic Hall coefficient obtained in transition-metal based magnetic systems. The cause for such a large EHE may be twofold: a strong spin–orbit interaction and a strong polarization of the Pt \(d\) states induced by Fe. It is noted that the resistivity of these Fe–Pt alloys is in the range of 20–70 \(\mu\Omega\) cm. The Hall angle defined by \(\tan \theta_0 = \rho_{xx}/\rho_{xy}\) is also very large.

The compositional dependence of \(R_4\pi M\) at 77 K is rather similar to that at 4.2 K. All samples remain ferromagnetic at 77 K. However, at \(T=285\) K, the \(x=10\%\) and 20\% samples are no longer ferromagnetic, thus suppressing the EHE. The peak of \(R_4\pi M\) shifts to \(x=40\%\). This is because the \(M\) of the \(x=40\%\) sample remains appreciable at 285 K, whereas the \(M\) of other Fe-poor samples is substantially reduced. Overall, the EHE remains robust at room temperature for samples with Fe content larger than 20\%.

In addition to the quantity \(R_4\pi M\), the initial Hall slope \((d\rho_{xy}/dH)\) before saturation is also an important quantity (see Fig. 3). As shown in Fig. 3, the initial \(\rho_{xy}\) is linear in \(H\). To achieve a large Hall slope it is preferred to have a small saturation field, which is equal to \(4\pi M\), when the magnetic field is perpendicular to a thin film as required for the Hall measurement. The Hall slope is presented in Fig. 5 as a function of Fe content. The maximum Hall slope, 6.9 \(\mu\Omega\) cm/T, is found in the \(x=30\%\) sample at \(T=285\) K. The Hall slope tends to be smaller at low \(T\) because of a larger \(M\) at low \(T\) and, hence, a larger saturation field. From the maximum Hall slope, we can estimate an effective carrier concentration ("\(n\)") if the EHE was caused by the normal Hall effect. The value of "\(n\)" is about \(5\times10^{19}/\text{cm}^3\). The large Hall slope observed in the Fe–Pt series is, to our knowledge, among the largest in transition-metal based magnetic systems. Compared with a normal metal such as Cu, the Hall slope in the Fe–Pt alloys is enhanced by three orders of magnitude.

1 See, e.g., Reviews in Phys. Today 48, 58 (April, 1995).