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ABSTRACT

The anomalous Nernst effect (ANE) in disordered Fe0.5(Pt0.5Pd0.5)x alloy films is investigated at room temperature. The spin orbit coupling (SOC) strength is continuously tuned by changing the composition of Pt and Pd in Fe0.5(Pt0.5Pd0.5)x alloy films. It was found that the ANE voltage \( V_{ANE} \) increases with the increase of Pt composition. Meanwhile, the \( v_N \) factor, which indirectly represents the anomalous Nernst efficiency, also increases with raising the composition of Pt. The enhancement of \( V_{ANE} \) and \( v_N \) at larger \( x \) can be attributed to the increasing of SOC strength, which mainly comes from heavy Pt atoms. The present results will facilitate the theoretical studies of ANE and provide means of manipulating ANE for technological application.

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I. INTRODUCTION

With higher degree of integration for the electronic devices, it is very struggling to further miniaturize the devices due to the local Joule heat. Therefore, the proper absorption and utilization of waste heat become the key points to develop high-efficiency and low-power consumption information technology. Recently, spin-caloritronics, one of the most important branches of spintronics, attracts intensive research interest. Spin-caloritronics focuses on the interaction among charge current, heat flow as well as spin current. It provides an effective way in recycling the waste heat in spintronics devices. Many related phenomena such as spin Seebeck effect, thermal spin-transfer torque, spin Nernst effect have emerged. These effects take full advantage of the transport of spin moment and electron charge under temperature gradient.

Anomalous Nernst effect (ANE) is one of the most significant phenomena in spin-caloritronics. It generates an electric voltage in the cross product direction between the magnetization and temperature gradient in a ferromagnetic material. So it is also a thermolectric form of anomalous Hall effect (AHE). The ANE electric field can be expressed as

\[
\vec{E}_{ANE} = Q_{S0} (M \times \nabla T)
\]

here \( \mu_0 \) and \( Q_0 \) are vacuum permeability and anomalous Nernst coefficient, respectively. The ANE was studied in many ordered alloy system with perpendicular anisotropy. Some researches demonstrate that ANE has a tendency to increase with perpendicular uni-axial magnetic anisotropy which is correlated to SOC. Moreover, ANE voltage was found to increase with an increasing in the number of interfaces in [Pt/Co]n multilayers, in which the SOC is dominated by interfaces. Just like AHE, ANE also originates from SOC. However, the quantitative dependence of the ANE on the SOC strength is still unclear. In order to enhance the ANE, it is imperative to study ANE in ferromagnetic materials in which the SOC strength can be tuned continuously in a wide range.

In this work, magnetic disordered ternary Fe0.5(Pt0.5Pd0.5)x alloy films with various Pt/Pd concentrations were chosen to study the SOC tuning effect on the ANE. The SOC can be continuously tuned by changing the Pt/Pd concentration, whereas other physics properties, such as the lattice constant, saturation magnetization and band structure at Fermi level are almost fixed. The disordered FePtPd alloy films pertain to soft magnetic materials. So...
this work will provide a promising way to enhance the ANE in soft magnetic materials.

II. EXPERIMENTS

A series of Fe$_{0.5}$(Pt$_x$Pd$_{1-x}$)$_{0.5}$ films were fabricated on glass substrates at room temperature by DC magnetron sputtering from a composite target with small Pt or Pd pieces (6 mm × 6 mm × 1 mm) placed evenly on a pure 99.99% Fe target. The size of glass substrate is 1.5 mm × 6.5 mm. The Pt/Pd concentration was controlled by changing the numbers of Pd and Pt pieces. The base pressure was lower than 1.8 × 10$^{-5}$ Pa before sputtering. The FePtPd layers were deposited under the working Ar pressure of 0.6 Pa and DC sputtering power of 40 W. The deposition rate of FePdPt is around 0.13 nm/s. The film thickness and microstructure were characterized by X-ray reflection (XRR) at small angles and X-ray diffraction (XRD) at high angle by a Bruker D8 diffractometer with Cu K$_\alpha$ radiation of λ=1.5419 Å, respectively. The composition of the films was characterized by energy dispersive spectroscopy (EDS). The hysteresis loops of thin film were measured by the vibrating sample magnetometer (VSM) of Lakeshore 7400. Films were patterned into rectangle shape in size of 1 mm × 6.5 mm for the electric transport measurement.

III. RESULTS AND DISCUSSIONS

Figure 1(a) shows the XRD spectra of all the FePtPd samples. The XRD peaks appear at 2θ = 41° correspond to the (111) orientation of the disordered FePt$_x$Pd$_{1-x}$ thin films, of which the structure is face-centered cubic (FCC). Except for FePtPd (111) peaks, no peaks can be found in other 2θ ranges. The FePt$_x$Pd$_{1-x}$ (111) peaks shift to high angle with increasing the composition of Pt, indicating the lattice constant gets smaller when $x$ is close to 1, as shown in Fig. 1(b). The film thickness and roughness were measured by XRR, as shown in Fig. 1(c). The films were measured to be 20±2 nm, except for FePt film with 16.4 nm in thickness. The roughness of the interface is 0.9±0.1 nm for the fabricated films. In-plane magnetization hysteresis loops for selected samples were measured at room temperature via VSM as shown in Figure 1(d). The spontaneous magnetization was found to be 980±40 emu/cm$^3$, close to that of the L$_{10}$ FePtPd. The coercivity is about 30 Oe for all samples.

The ANE was measured by a custom-made thermal-electrical transport measurement system. Since the easy magnetization direction of the disordered FePtPd is in-plane, the orientation of applied magnetic field and temperature gradient should be in-plane and out of plane during the measurement of ANE, respectively, as shown in Figure 2(a). A fixed resistor chip with the resistance of 100 Ω at ambient temperature is used to be the heater. The heater is connected to a 1.5 mm thick thermally conductive silicone pad. Here the thermally conductive pad is used to avoid electrical contact of the heater with the sample. The sample is placed on the Cu plate. The Cu plate provides the heat sink and is contacted with the refrigerator (Sumitomo model RDK 101D) in order to keep a stable temperature. Joule heat will be produced by applying an electric DC current to the heater via Keithley 2400 sourcemeter. Then the temperature gradient normal to the film plane is formed between the heater and Cu plate. The ANE voltage is measured by Keithley 2182A nanovoltmeter in the $x$ direction, as shown in Fig. 2(a).

Figure 2(b) displays several representative sets of the voltage vs $H$ curves measured at different heating current for Fe$_{0.5}$(Pt$_{0.3}$Pd$_{0.7}$)$_{0.5}$ film. In order to reduce the systematic errors, each sample was installed and measured repeatedly for 6 times. All the curves evolve in a magnetic hysteresis loop like shape. The anomalous Nernst voltage $V_{ANE}$ was deduced by $(V^+ - V^-)/2$, where $V^+$ and $V^-$ were extrapolated from the linear dependence of $V$ at positive and negative high $H$, respectively. The temperature of the Cu plate was kept at 300 K.
When heating current $I$ applied to the heater is larger, the temperature gradient $\nabla T$ will be enhanced, which results in stronger $V_{\text{ANE}}$. As shown in Fig. 2(c), $V_{\text{ANE}}$ increases nonlinearly with the heating current $I$ applied to the heater. Since the Joule heat with power $P=I^2R_{\text{he}}$ is directly related to the temperature gradient $\nabla T$, the $V_{\text{ANE}}$ is measured to increase linearly with the heating power $P$, as shown in Fig. 2(d). Here $R_{\text{he}}$ is the resistance of the heater.

For all the samples, the $V_{\text{ANE}}$ increases linearly with the heating power, as shown in Fig. 3(a). At each specific heating power, the $V_{\text{ANE}}$ increases by 3 times from FePd to FePt. Considering the small magnitude temperature gradient $\nabla T$ along the normal direction of the thin film, and the influence of thermal conductivities from different samples on $\nabla T$, it is hard to determine $\nabla T$ and directly confirm the anomalous Nernst coefficient $Q_S$ in this work. According to the linear dependences of $V_{\text{ANE}}$ on both heating power $P$ and $\nabla T$, it is reasonable to suppose that the $\nabla T$ is positive correlated to the heating power $P$. Then the factor $\nu_N = dV_{\text{ANE}}/dP$ is defined to indirectly characterize the ANE coefficient.$^{19}$ Figure 3(b) shows the factor $\nu_N$ for each sample. One can see that $\nu_N$ increases from 13.2$\pm$0.7 $\mu$V/W for FePd to 37$\pm$0.7 $\mu$V/W for FePt. The magnitude of both $V_{\text{ANE}}$ and $\nu_N$ are enhanced from FePd to FePt by almost 3 times.

It is significant to address the dependence of the ANE on the SOC strength. The ANE is found to increase with the uniaxial magnetic anisotropy $K_u$ in the ordered alloy thin films.$^{15}$ The $K_u$ is well known to be related to the SOC.$^{23,24}$ So it indirectly proves that the ANE increases with SOC strength. On the other hand, both the ANE and AHE are thought to be originated from SOC. The relations

**FIG. 2.** (a) The schematic of the ANE measurement. (b) The voltage versus in-plane field $H$ at various heating current, (c) the ANE voltage $V_{\text{ANE}}$ versus heating current $I$ and (d) $V_{\text{ANE}}$ versus heating power $P$ for Fe$_{0.5}$(Pt$_{0.3}$Pd$_{0.7}$)$_{0.5}$ sample. The red line in (d) is the fitting line.

**FIG. 3.** (a) Heating power $P$ dependences of the ANE voltage $V_{\text{ANE}}$ for all the samples. (b) The factor $\nu_N$ versus Fe composition $x$. 

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between AHE, ANE and SOC are reported for several materials.\textsuperscript{25,26} The anomalous transport parameters in AHE and ANE are proved to be linked by the Mott relation.\textsuperscript{13,21} With the composition of Pt increasing in either ordered or disordered FePtPd alloy films, the AHE is found to be enhanced due to the increasing of SOC.\textsuperscript{20,21} So it is reasonable to say that the enhanced \( V_{ANE} \) and \( V_N \) at high x are attributed to the larger SOC strength of Pt atoms compared with that of Pd atoms.\textsuperscript{27} Previous calculations have already shown that the SOC strength \( \xi \) in the ordered alloys on Pd/Pt-site changes from 0.19 eV/cm\(^2\) to 0.58 eV/cm\(^2\) when Pt/Pd concentration \( x \) changes from 0 to 1.0 in L1\(_0\) FePtPd alloy films.\textsuperscript{20,21} The ratio \( V_N \) (FePt)/\( V_N \) (FePd) in this work is 2.8, close to the ratio \( \xi \) (Pt)/\( \xi \) (Pd), directly proving the tuning effect of SOC on ANE. It is worth to mention that in the previous study of AHE in FePtPd alloy, the intrinsic anomalous conductivity of FePt is about four times larger than that of FePd, which slightly deviates from the ratio \( \xi \) (Pt)/\( \xi \) (Pd). That is because in the AHE experiment, the sheet resistance should be considered. However, in the ANE experiment, the variation of sheet resistance can be neglected as it is an open circle measurement. The present work shows the advantage of ANE methods, and are believed to be helpful to address the effect of SOC on ANE in soft magnetic materials.

IV. CONCLUSIONS

In summary, we have studied the ANE in disordered FePtPd alloy films. The ANE voltage \( V_{ANE} \) increases linearly with the heating power applied to the heater, indicating \( V_{ANE} \) is proportional to the temperature gradient. Both the \( V_{ANE} \) and \( V_N \) factor can be continuously tuned by replacing Pd atoms with heavier Pt ones. The enhancement of \( V_{ANE} \) and \( V_N \) at larger x can be attributed to the increasing of SOC strength \( \xi \), which mainly comes from heavy Pt atoms. The present work will stimulate theoretical investigation on the ANE in magnetic disordered alloys with easy magnetization axis in-plane. It will also provide a new clue to enhance the ANE and optimize the ANE-based spintronics devices.

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