Influence of disorder on spin-orbit torques in perpendicularly magnetized FePt single layer

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Abstract:

We report the disorder-dependent spin-orbit torques (SOT) in 3-nm-thick FePt single layer grown on MgO (001) substrate. With varying growth temperatures, perpendicularly magnetized FePt films with different ordering have been achieved. The magnetization can be almost completely switched for the films with enormous disorder, while very small percent of magnetization can be switched for the films with the mixture of fully $L1_0$ ordered and poor chemical ordering. Through harmonics measurements, we have found that the spin Hall angle is larger for the mixed ordered FePt film, indicating larger spin current generation efficiency. However, in this film, the complicated magnetization dynamics due to the mixture of fully $L1_0$ ordered and poor chemical ordering has impeded the magnetization switching. This finding illustrates the efficiency of SOT in FePt single layer is much dependent on the disorder.

Keywords: Spin-orbit torque; Perpendicular magnetic anisotropy; Spin transport; Disorder

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In recent years, the interest in magnetic materials and heterostructures with strong spin-orbit coupling (SOC) has substantially intensified, which plays a fundamental role in a number of phenomena, including magnetocrystalline anisotropy, current-induced spin-orbit torques (SOT), anomalous Hall effect (AHE), spin Hall effect (SHE) as well as the formation of chiral magnetic textures. The SOT, which mediates the transfer of angular momentum from the lattice to the spin system, has been widely investigated as they can provide efficient and versatile ways to control magnetization dynamics in different classes of materials, including noncentrosymmetric ferromagnets (FM), antiferromagnets, topological insulators and heavy metal (HM)/FM heterostructures.1-8 Two main model mechanisms have been proposed to generate SOT.9-15 The spin current generated by the SOC due to SHE will propagate toward the interface and is absorbed in the form of a magnetization torque in the adjacent FM. In the other model scenario, a charge current flowing parallel to an interface with broken inversion symmetry will induce the accumulated spins due to SOC at the interface and force the moments of the adjacent FM layer to change their direction by direct exchange coupling. Both of the two mechanisms can lead to the exertions of damping-like torques and field-like torques on the FM layer, which can be characterized by equivalent damping-like effective field \( H_D \) and field-like effective field \( H_F \), respectively.16

In general, the SOT has been most extensively studied experimentally in the HM/FM bilayer (or multilayer) structures with interface-induced perpendicular magnetic anisotropy (PMA), which present three major limitations.17, 18 First, from a materials perspective, the typically elemental FMs Fe, Co, and Ni have the disadvantage of weak SOC with corresponding small values of magnetic anisotropy energy. Therefore, the presence of nonmagnetic HM in HM/FM interfaces modifies the interfacial orbital angular momentum of the transition metal and enhances its SOC, thereby increasing the PMA. On the other hand, however, both the SHE and the Rashba effect overlook the details of the interfacial orbital overlap, which can be quite subtle in HM/FM interfaces and lead to enhanced orbital magnetization and related spin-orbit phenomena. Finally, in the commonly used bilayers with a nm-scale
spin-diffusion length and nm-thick magnetic film, the distinction between SOT generated by “bulk”-SHE and “interface”-Rashba effect remains principally blurred.

To overcome these issues, we have investigated the SOT in single FePt layer with PMA, which is a classical example of a complex FM which combines strong SOC due to the emergence of Pt and strong ferromagnetic ordering.\textsuperscript{19-21} The strong SOC in combination with uniaxial symmetry of the tetragonal crystal structure leads to a gigantic bulk PMA. In this work, we have realized the current-induced SOT in FePt single layer and investigated the impact of disorder on the SOT. With varying growth temperatures, perpendicularly magnetized FePt films with different ordering have been achieved. We have found that the efficiency of SOT in FePt single layer is dramatically dependent on the disorder of the films.

The 3-nm-thick FePt films were epitaxially deposited on MgO (001) substrates by magnetron co-sputtering from Fe and Pt elemental targets at different growth temperatures, where the base pressure of the sputtering chamber was less than $8\times10^{-6}$ Pa. The substrates were kept at different growth temperatures $T$ varying from 350 °C to 400 °C. After deposition, the 3-nm-thick FePt films were annealed in situ at the same growth temperature for 2 hours, and then the samples were left to cool to room temperature in situ. The magnetic properties of the FePt films with different growth temperatures were measured via VSM magnetometry at room temperature. The in-plane and out-of-plane normalized M-H curves of the films with $T=350$ °C and $T=400$ °C are given in Fig. 1(a) and 1(b), respectively. The magnetic easy axes are perpendicular to the film plane for the two samples. On the other hand, to evaluate the PMA properties quantitatively, the uniaxial magnetic anisotropy $K_U$ was estimated using the relations $K_U=M_3H_K/2$. Here, the anisotropy field $H_K$ was defined as the extrapolated intersection of the in-plane M-H curve with the saturation magnetization value of the out-of-plane M-H curve. Table I shows the values of the films with $T=350$ °C and $T=400$ °C. It is found that the film with $T=350$ °C shows low saturation magnetization of 800 emu/cc, low coercivity of 500 Oe and small uniaxial magnetic anisotropy of $0.4\times10^7$ erg/cc. The values are all much different from the fully ordered FePt alloys ($M_s\sim1100$ emu/cc, $K_U\sim7\times10^7$ erg/cc),\textsuperscript{22} which is thought to arise from the
enormous insufficient $L1_0$ ordering, in other words the existence of complicate antisite defects between Fe and Pt atoms. On the other hand, the $K_U$ of the film with $T=400 \, ^\circ C$ becomes larger but the magnetization curve shows a step of the perpendicular magnetization curve around zero magnetic field, which is thought to arise from the mixture of fully $L1_0$ ordered and poor chemical ordering as described before.

A Hall bar of 20 $\mu$m×120 $\mu$m was patterned for electrical measurement by electron beam lithography and Ar ion milling, and a lift-off process was used to form contact electrodes. The schematic of the Hall bar along with the definition of the coordinate system used in this study is shown in Fig. 1(c). A scanning electron microscope (SEM) image of the patterned Hall bar and the schematic of the setup measurement is shown in Fig. 1(d). Figure 2 show the magnetic field dependence of anomalous Hall resistance ($R_H$) and current-induced magnetization switching behaviors ($R_I$) at room temperature for FePt with $T=350 \, ^\circ C$, $T=370 \, ^\circ C$ and $T=400 \, ^\circ C$. As increasing growth temperature $T$ from 350 $^\circ C$ to 400 $^\circ C$, the anomalous Hall resistance $R$ in FePt film is significantly decreased from 24 $\Omega$ to 10 $\Omega$. It should be noted that all the three devices have similar longitudinal resistance (~600 $\Omega$). The anomalous Hall resistance is roughly proportional to the magnetization. However, the largest $M_S$ while smallest $R$ for FePt with $T=400 \, ^\circ C$ indicate that the microscopic mechanisms of AHE should depend on the ordering of FePt. Both the anomalous Hall effect (AHE) and SHE originate from three distinct microscopic mechanisms that they all share: the skew, the side jump, and the intrinsic mechanisms. The mechanisms are caused by coherent band mixing effects induced by the external electric field and the disorder potential.23, 24 Among the three contributions, the easiest to evaluate accurately and the one that has dominated most theoretical studies is the intrinsic contribution. The induced interband coherence is captured by an anomalous velocity arising from a momentum-space Berry phase. In general, the intrinsic contribution to the AHE is dependent only on the band structure of the perfect crystal. Therefore, the larger anomalous Hall resistance $R$ in FePt film ($T=350 \, ^\circ C$) with larger antisite defects should stem from the extrinsic scattering contribution. The current-induced magnetization switching behaviors in FePt films were measured by applying a pulsed
current with the width of 50 µs, and the resistance was measured after a 16 µs delay under an in-plane field $H_x$ at room temperature. It should be noted that we have selected the SOT results for each film with relatively largest ratio of magnetization switching via varying $H_x$. As compared with the Hall resistance as shown in Fig. 2(a), almost 88 % of the magnetization in FePt film with $T=350$ °C can be switched when $H_x=500$ Oe as shown in Fig. 2(b). The critical switching current $I_c$ is 15 mA. Here, $I_c$ is defined as the current when the resistance is zero after processing the SOT data to make it symmetric about the X axis. The ratio of magnetization switching decreased to ~60 % with $H_x$ is 400 Oe as shown in Fig. 2(d) for FePt film with $T=370$ °C, and the $I_c$ is 30 mA. Markedly, only 10 % of the magnetization in FePt film with $T=400$ °C can be switched when $H_x=1000$ Oe as compared with the R-H curves. It is indicated that the SOT in FePt single layer is very sensitive to the ordering of the films. There are two possible underlying scenarios of the disorder dependent SOT in the FePt films: (i) the different spin current generation efficiency in the films; (ii) the complicated magnetization dynamics due to the mixture of fully $L1_0$ ordered and poor chemical ordering.

From the materials’ perspective, the spin current should be primarily generated by SHE model mechanism since the unit cell of FePt alloy is locally centrosymmetric and the Rashba SOC is weak. As mentioned, the SHE borrows directly from the physics and mechanisms of the AHE and correspondingly much of their descriptions are parallel. Pictorially, intrinsic contribution to the SHE arise from the nonequilibrium electron dynamics of the Bloch electrons as they are accelerated in an electric field and undergo spin precession due to the induced momentum-dependent magnetic field. The skew-scattering contribution to the SHE is the mechanism proportional to the Bloch state transport lifetime. It will therefore tend to dominate in nearly perfect crystals. Therefore, both the intrinsic and the skew-scattering contributions should not be the origin of the spin current in FePt with enormous disorder. When addressing materials with strong SOC, it is important to remember that there are always two sources of side-jump scattering: (1) The contribution arising from the non-spin-orbit-coupled part of the wave-packet scattering off the
spin-orbit-coupled disorder. (2) The contribution arising from the spin-orbit-coupled part of the wave packet formed by the Bloch electrons scattering off the scalar potential alone without SOC. The two sources of side-jump scattering depend on the crystalline environment and the type of scattering impurity. In HMs, such as Pt, Ta and W, the dominant contribution is likely to be the second type of contribution. In FMs, it has been demonstrated that the second type of contribution, termed here intrinsic side jump to distinguish them clearly, can be very large. Both of these two contributions are independent of the Bloch state transport lifetime. Therefore, we infer that the spin current in FePt films with enormous disorder mainly stem from the side-jump scattering, and the generation efficiency due to the intrinsic and the skew-scattering contributions will become large in more ordered FePt films.

To improve our speculation and quantitatively investigate the influence of the disorder on the SOT in FePt films, the harmonic measurements with sweeping large and small in-plane magnetic fields $H_x$ and $H_y$ (parallel or perpendicular to the current direction) were carried out at room temperature. The measured first $V_\omega$ and second $V_{2\omega}$ harmonic Hall voltages with applying a sinusoidal AC current with the amplitude of 3 mA in FePt film with $T=350^\circ$C were plotted against $H_x$ and $H_y$ in Fig. 3, and the Hall voltage signals were detected by two lock-in amplifier systems simultaneously. The $V_\omega$ with magnetic field sweeps along X and Y are almost the same as shown in Fig. 3(a) and 3(c), respectively. As shown in Fig. 3(b), $V_{2\omega}$ shows a negative peak at a positive magnetic field and a positive peak at a negative magnetic field when the magnetic field sweeps along direction X. As shown in Fig. 3(d), two negative peaks of $V_{2\omega}$ around the zero magnetic field when the magnetic field sweeps along direction Y. These odd and even behaviors of $V_{2\omega}$ when the magnetic field sweeps along the direction X and Y indicate that both the damping-like and field-like torques exist in the films, and only the damping-like torque depends on the magnetization direction. Furthermore, the first $V_\omega$ and second $V_{2\omega}$ harmonic Hall voltages against a smaller in-plane magnetic field $H_x$ and $H_y$ were also measured at room temperature as well. Before the harmonic measurements, we have applied a large out-of-plane external field $M_z$ to saturate the magnetization of FePt film, which remain saturated after the
field is turned off. The results of measurements by applying a sinusoidal AC current with an amplitude of 3 mA are shown in Fig. 4, in which the signals are measured with the out-of-plane magnetization component \( M_z > 0 \) and \( M_z < 0 \). The damping-like effective fields \( H_D \) and field-like effective fields \( H_F \) can be calculated by the following equation:25-27

\[
H_{D(F)} = -2 \frac{H_{L(T)} \pm 2 \xi H_{T(L)}}{1 - 4 \xi^2}
\]  

(1)

where the \( \xi \) is the ratio of planar Hall effect (PHE) resistance and anomalous Hall effect (AHE) resistance and the \( \pm \) sign is the magnetization pointing \( \pm Z \). The \( H_{L(T)} \) can be determined using the following equation:

\[
H_{L(T)} = -\frac{\partial V_{2o}/\partial H_{X(Y)}}{\partial^2 V_o/\partial H_{X(Y)}^2}
\]  

(2)

The value of \( \xi \) have been determined through the PHE measurement under an in-plane magnetic field of 3 T. \( R_{PHE} \) can be acquired by the method in Ref.27,28, and the value of \( \xi \) is -0.052. Using Equations (1) and (2), the \( H_D \) and the \( H_F \) for FePt film with \( T=350 \) °C are determined to be 7.086 Oe and 4.559 Oe, respectively. The effective spin Hall angle \( \theta_{SH} \) of FePt film with \( T=350 \) °C can be extracted using the following equation:29

\[
\theta_{SH} = \frac{2|e| M_S t_F H_D}{\hbar j}
\]  

(3)

where \( e \) is the charge of an electron, \( j \) is charge current density, \( t_F \) is the thickness and \( M_S \) is the saturation magnetization of FePt film. Finally, the effective spin Hall angle \( \theta_{SH} \) is calculated to be 0.067. Using the same method, we have also determined the values for FePt film with \( T=400 \) °C, the \( H_D, H_F \) and \( \theta_{SH} \) are 5.3 Oe, 1.2 Oe and 0.095 respectively.

It is found that the spin Hall angle is larger for FePt film with \( T=400 \) °C, indicating a larger spin current generation efficiency. However, the magnetization for this film can be switched in very small percentage. The harmonic measurements for FePt films with \( T=370 \) °C and \( T=400 \) °C were carried out with sweeping a large in-plane magnetic field \( H_x \) and \( H_y \) and the same magnitude of AC current (3 mA). The
second $V_{2\omega}$ harmonic Hall voltages of FePt film with $T=370$ °C are shown in Fig. 5(a) and 5(b). With sweeping the magnetic field along the current flow direction X, $V_{2\omega}$ has an odd behavior, which is similar to the results in FePt film with $T=350$ °C. However, the even behavior of $V_{2\omega}$ is not obvious when the magnetic field sweeps along direction Y as shown in Fig. 5(b), indicating a small field-like torque and complicated magnetization dynamics. It becomes more evident for FePt films with $T=400$ °C as shown in Fig. 5(c) and 5(d). Both the $V_{2\omega}$-$H_x$ and $V_{2\omega}$-$H_y$ curves become nonsymmetrical, indicating more complicated magnetization dynamics due to the mixture of fully $L1_0$ ordered and poor chemical ordering. In other words, although a larger spin current has been generated for FePt film with higher growth temperature, the magnetization cannot be switched efficiently due to the mixed chemical ordering.

In summary, we have compared and investigated the current-induced magnetization switching in 3-nm-thick FePt single layer with different ordering. The magnetization can be switched more fully and the critical switching currents $I_c$ is smaller in FePt film with enormous disorder. With harmonics measurements, we have found that although a larger spin current has been generated for FePt film with higher growth temperature, the magnetization cannot be switched efficiently due to the mixed chemical ordering. Two mechanisms determine the disorder-dependent SOT in the FePt films: (i) the disorder-dependent spin current generation efficiency; (ii) the complicated magnetization dynamics due to the mixture of fully $L1_0$ ordered and poor chemical ordering.

**Data Availability Statement:** The data that support the findings of this study are available from the corresponding author upon reasonable request.

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TABLE I. Growth temperature $T$, saturated magnetization $M_S$, anisotropy field $H_K$, uniaxial magnetic anisotropy $K_U$ for the two FePt films.

| $T$ (K) | $M_S$ (emu/cc) | $H_K$ (T) | $K_U$ ($\times 10^7$ erg/cc) |
|---------|----------------|-----------|-------------------------------|
| 350     | 800            | 1         | 0.4                           |
| 400     | 1600           | 1.5       | 1.2                           |

FIG. 1. Normalized M-H curves for the FePt films with $T=350$ °C (a) and $T=400$ °C (b). (c) Geometric configurations of Hall bar along with the definition of the coordinate system. (d) The SEM image of a patterned Hall bar and schematic of the setup measurement.

FIG. 2. The magnetic field dependent anomalous Hall resistance of FePt films with $T=350$ °C (a), $T=370$ °C (c) and $T=400$ °C (e). The current-induced magnetization switching behaviors of FePt films with $T=350$ °C (b), $T=370$ °C (d) and $T=400$ °C (f), and the $H_x$ is 500 Oe, 400 Oe and 1000 Oe, respectively.

FIG. 3. The first $V_{\omega}$ and second $V_{2\omega}$ harmonic Hall voltages plotted against the large in-plane external fields $H_x$ and $H_y$ in FePt film with $T=350$ °C.

FIG. 4. The first $V_{\omega}$ and second $V_{2\omega}$ harmonic Hall voltages plotted against the small in-plane external fields $H_x$ and $H_y$ in FePt films with $T=350$ °C. The black and red signals are measured with the out-of-plane magnetization component $M_z > 0$ and $M_z < 0$, respectively.

FIG. 5. The second $V_{2\omega}$ harmonic Hall voltages plotted against the large in-plane external fields $H_x$ and $H_y$ in FePt films with $T=370$ °C and $T=400$ °C.
