Current-induced magnetization switching in a chemically disordered A1 CoPt single layer

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We report the first demonstration of current-induced magnetization switching in a perpendicularly magnetized A1 CoPt single layer. We show that good perpendicular magnetic anisotropy can be obtained over a wide composition range of A1 Co1−xPtx single layers, which allows the fabrication of a perpendicularly magnetized CoPt single layer with a composition gradient that breaks the inversion symmetry of the structure. By fabricating a CoPt single layer with a gradient, we were able to evaluate spin-orbit torque (SOT) efficiency and successfully realize SOT-induced magnetization switching. Our study provides an approach for realizing current-induced magnetization in ferromagnetic single layers without attaching SOT source materials. © 2021 The Japan Society of Applied Physics

Current-induced magnetization switching through spin-orbit torques (SOTs) is essential for spin-orbital-based memory devices with low-energy consumption and high speed.1–13 Typically, in a heavy metal (HM)/ferromagnetic (FM) bilayer, SOTs can be generated through the bulk spin Hall effect in the HM layer and the Rashba effect at the HM/FM interface.14–23 When a charge current is applied, the generated SOTs transfer into the FM layer, and act as effective magnetic fields to manipulate the magnetization of the FM layer. Therefore, it has been considered that HMs or other SOT source materials are indispensable for generating SOTs and manipulating the magnetization of the FM layer. However, recent several studies have shown that current-induced magnetization switching can be realized in a single FM layer without attaching an HM layer.24–27 For instance, Tang et al. reported current-induced magnetization switching in an ordered L10 FePt single layer.23 They found that the inherent structural gradient in the film’s normal direction broke structural symmetry, was able to generate sizable SOTs, and was responsible for magnetization switching. Liu et al. also reported current-induced magnetization switching in an L10 FePt single layer due to the composition gradient.25 Zhang et al. reported current-induced magnetization switching in a CoTb amorphous single layer.26 Their interpretation was that the local broken inversion symmetry inside the layer was able to generate net SOTs and was responsible for the magnetization switching. Lee et al. studied SOT generation in CoTb single layers.27 Their interpretation was that the bulk spin-orbit interaction within the CoTb layer played a major role in SOT generation. Very recently, Zhu et al. reported SOT generation in a chemically disordered A1 CoPt single layer with in-plane magnetic anisotropy.28 Their interpretation was that SOTs are most likely generated by the spin Hall effect in the CoPt layer, since no long-range asymmetry was observed. However, in their study, a nonzero damping-like torque only existed at more than 8 nm, and no current-induced magnetization switching was studied. So far, an understanding of SOT generation and current-induced magnetization switching in FM single layers still remains elusive and is just beginning to be probed.

In this work, we report the first demonstration of current-induced magnetization switching in a perpendicularly magnetized A1 CoPt single layer. We show that good perpendicular magnetic anisotropy can be obtained over a wide composition range of A1 Co1−xPtx single layers, which allows the fabrication of a perpendicularly magnetized CoPt single layer with a composition gradient that breaks the inversion symmetry of the structure. By fabricating a CoPt single layer with a gradient, we were able to evaluate spin-orbit torque (SOT) efficiency and successfully realize SOT-induced magnetization switching.

For sample fabrication, Co1−xPtx single-layer films were deposited on MgO (111) single crystal substrates at 350°C by magnetron sputtering. The Co and Pt targets were co-sputtered at different powers to form Co1−xPtx with different composition ratios. The Co sputtering power was fixed at 30 W, and the Pt sputtering power was varied from 30 to 70 W. The concentration of Pt was calculated from the deposition rate at each sputtering power. The base pressure in the chamber before deposition was better than 1 × 10−6 Pa, and the deposition pressure was 0.4 Pa. During the sputtering, argon gas was supplied. The film thickness for each composition ratio was controlled by changing the deposition time at a precalibrated deposition rate. The crystal structures of the films were characterized by X-ray diffraction (XRD) with Cu Kα irradiation, and a vibrating sample magnetometer (VSM) was used to measure the magnetic properties. For the electrical transport measurements, the substrates were patterned into a Hall bar shape with width of 20 μm and length of 100 μm.

Figures 1(a)–1(e) demonstrate the anomalous Hall effect (AHE) hysteretic loops of 5 nm thick Co1−xPtx single layers with different compositions. Well-defined, square AHE hysteretic loops are present, indicating the good perpendicular magnetic anisotropy (PMA) of the Co1−xPtx. As can be seen, when the Pt concentration is increased, the AHE resistance of the Co1−xPtx gradually decreases, which confirms that the AHE signal is induced by Co magnetization. It is noteworthy that PMA is realized over a wide composition range from Co0.62Pt0.38 to Co0.41Pt0.59, which shows that the CoPt alloy has good tunability and its composition can be manipulated without sacrificing its...
PMA. Therefore, we can fabricate a CoPt single layer with a composition gradient that breaks the inversion symmetry of the structure. A 5 nm-thick Co\(_{1-x}\)Pt\(_x\) (x = 0.38 \(\rightarrow\) 0.59) single layer was fabricated. During its deposition, the Co sputtering power was fixed at 30 W, and the Pt sputtering power was continuously changed from 30 to 70 W by the sputtering controller. In the sputtering controller, by selecting an initial power of 30 W, an ending power of 70 W, and a deposition time period, the power is varied linearly from 30 to 70 W. Hereafter, we use ‘gradient CoPt’ to denote Co\(_{1-x}\)Pt\(_x\) (x = 0.38 \(\rightarrow\) 0.59). As shown in Fig. 1(f), the 5 nm thick gradient CoPt single layer exhibits good PMA.

The CoPt alloy has three main structural phases, which are the A1 phase, the L1\(_1\) phase, and the L1\(_0\) phase. The A1 phase is a face-centered cubic (fcc) structure with each position randomly occupied by a Co or Pt atom.\(^{29}\) The L1\(_1\) phase is a rhombohedral structure with each atomic layer alternately occupied by Co and Pt atoms in the [111] direction.\(^{30}\) The L1\(_0\) phase is a face-centered tetragonal (fct) structure with each atomic layer alternately occupied by Co and Pt atoms in the [100] direction.\(^{31}\) First, we can rule out the L1\(_0\) phase in our Co\(_{1-x}\)Pt\(_x\), since the formation of the L1\(_0\) phase requires a much higher deposition/annealing temperature (~700° C).\(^{24,31}\) Moreover, only (001)-oriented L1\(_0\) CoPt exhibits PMA, but since we used MgO (111) substrates, the Co\(_{1-x}\)Pt\(_x\) was only able to grow epitaxially in the [111] direction. To investigate whether the crystal structure of the Co\(_{1-x}\)Pt\(_x\) in our study is the chemically disordered A1 phase or the ordered L1\(_1\) phase, we conducted XRD measurements. As shown in Fig. 2, besides the MgO (111) peak, a peak located at around 41° can be observed. This peak can be attributed to the A1 CoPt (111) peak or the L1\(_1\) CoPt (222) peak.\(^{30}\) However, the representative L1\(_1\) CoPt (111) peak, which is located at around 21°, cannot be observed. Thus, we can confirm that the Co\(_{1-x}\)Pt\(_x\) is the A1 phase, and the peak at around 41° is the A1 CoPt (111) peak. It is noteworthy that when the Pt concentration is increased, the A1 CoPt (111) peak gradually shifts to a smaller angle, which is consistent with its composition, since the Pt (111) standard peak is located at around 40°.\(^{30}\) The PMA in our A1 Co\(_{1-x}\)Pt\(_x\) single layer is induced by magnetoelastic anisotropy. Since the lattice constants of the MgO (111) substrate and CoPt (111) crystal are 2.978 Å and 2.692 Å, internal tensile stress is induced in the CoPt layer due to the large lattice mismatch (9.6%), which favors the PMA.\(^{29}\)

In the following, we evaluate SOT generation in uniform gradient CoPt. By applying an AC current, we were able to measure the second-harmonic AHE resistance as a function of an in-plane external magnetic field using lock-in amplifiers, as shown in Fig. 3. The measured data was fitted by the formula \(R_{2\omega} = -R_H H_{\omega} / 2(H_x - H_K)\) in the data range where the magnetization was totally aligned with the external magnetic field.\(^{6}\) Here, \(R_H\) is the out-of-plane saturation AHE resistance, \(H_{\omega}\) is the effective SOT field induced by the AC current, and \(H_K\) is the magnetic anisotropic field. The \(R_H\) values obtained were 0.73 \(\times\) 10\(^{-11}\) Oe A\(^{-1}\) m\(^2\) in the Co0.50Pt0.50, and 2.31 \(\times\) 10\(^{-11}\) Oe A\(^{-1}\) m\(^2\) in the gradient CoPt single layers. Furthermore, the SOT generation efficiency can be estimated by the formula

\[
\eta = \frac{SOT}{R_H H_{\omega}}
\]

where \(SOT\) is the SOT generation efficiency and \(R_H H_{\omega}\) is the effective driving field. The SOT generation efficiency was calculated to be 0.73 \(\times\) 10\(^{-11}\) m\(^2\) Oe A\(^{-1}\) in the Co0.50Pt0.50, and 2.31 \(\times\) 10\(^{-11}\) m\(^2\) Oe A\(^{-1}\) in the gradient CoPt single layers. Furthermore, the SOT generation efficiency can be estimated by the formula

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be estimated by \( \xi = \frac{M_s H_{eff}}{2 e J_x} \), where \( M_s \), \( t \), and \( J_x \) are the saturation magnetization, CoPt thickness, Planck’s constant, and current density, respectively. \( \xi \) was calculated to be 0.009 for the Co0.50Pt0.50 and 0.028 for the gradient CoPt. The SOT efficiency in the gradient CoPt was more than three times larger than that of the Co0.50Pt0.50, indicating that the composition gradient broke the inversion symmetry of the structure and resulted in much larger SOT generation. This is consistent with previous studies of L10 FePt24,25) and amorphous CoTb26).

Because of the existence of the sizable SOT in the gradient A1 CoPt, current-induced magnetization switching is expected in the A1 CoPt single layer. Thus, we measured \( R_H \) by sweeping an in-plane DC current \( I_{dc} \). For this measurement, an in-plane magnetic field \( H_x \) was applied to break the rotational symmetry of the SOT [see Fig. 4(a)]. As shown in Fig. 4(b), by applying a nonzero \( H_x \), the current switches the magnetization of the gradient CoPt single layer between the up and down directions; the polarity of the magnetization switching is reversed by reversing the direction of \( H_x \), which is consistent with the magnetization switching induced by the SOT. We also conducted the same measurement for a Co0.50Pt0.50 single layer. However, no magnetization switching was observed [see Fig. 4(c)]. This is consistent with the SOT measurement and shows that a low SOT efficiency is not sufficient to switch the magnetization in the uniform CoPt single layers, as it has no inversion asymmetry.

In summary, we have demonstrated current-induced magnetization switching in a perpendicularly magnetized A1 CoPt single layer. We have shown that good PMA can be obtained over a wide composition range, which allows the fabrication of a perpendicularly magnetized CoPt single layer with a composition gradient that breaks the inversion symmetry of the structure. It was found that the SOT efficiency of the gradient A1 CoPt was much larger than that of a uniform Co0.50Pt0.50 single layer. Thanks to the sizable SOT generation, SOT-induced magnetization switching was successfully realized in the gradient A1 CoPt single layer. Our study provides an approach for realizing current-induced magnetization in FM single layers without attaching SOT source materials.

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