Spin-orbit torque induced reversible coercivity change in Co/Pd multilayer thin films

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Abstract

In this work, we report reversible reduction in coercivity of Co/Pd multilayer thin films under high-density direct current biasing. We carried out in-situ focused magneto optic Kerr effect based hysteresis measurement while the specimen was under DC bias. The experiments show a reversible reduction in coercivity during the application of direct current. We propose this reduction occurs due to the field like spin-orbit torque generated by spin Hall effect. These results are further supported by the anomalous Hall effect measurement, which do not show any change in coercivity. The magneto-optic Kerr measurement probes the surface (penetration depth) whereas anomalous Hall effect is a bulk transport behavior. These complimentary measurements prove that the origin of spin-orbit torques in ferromagnetic metal/ heavy metal multilayer thin films is spin-Hall effect.

Keywords- (A) Cobalt Palladium multilayer

(B) Magneto optic Kerr effect

(C) Spin orbit torque

(D) Spin Hall effect

Introduction

Current-induced spin-orbit torques in ferromagnetic thin films are considered to be one of the prime candidate for the use of low-power device applications[1-5]. Spin-orbit torques may results from the spin-Hall effect as well as Rashba effect[5-8]. The heavy metals (Pt, Pd and Ta) are observed to show the spin-Hall effect (SHE) and are touted as a source of pure spin current [9-11]. In ferromagnetic (F)/ heavy metal (HM) multilayer systems, SHE can induce spin-orbit torques[12]. The momentum-dependent splitting of spin bands in two-dimensional heterostructures is found to be a combination of atomic spin-orbit coupling and asymmetry of the potential in the direction perpendicular to the two-dimensional plane and is given the name Rashba effect[13]. The Rashba effect has been proposed as the mechanism to explain the current-induced torques with an in-plane current for many nanomagnetic devices[14-16]. Further, the spin polarization and the interface current are found to be significantly enhanced because of the Rashba-Dresselhaus effect[17]. I. M. Miron et al. investigated current-driven spin torque induced by the Rashba effect and found that an electric current flowing in plane of the Co layer with asymmetric Pt and AlO_x interfaces produces an effective transverse magnetic field of 1T per 10^8 A/cm^2 . They proposed that this was due to the combination of spin-orbit and exchange interactions due to the Rashba effect [18]. Using various experimental techniques (primarily electrical), the effects of spin-orbit torques have been measured over the years [6, 19, 20]. However, there is uncertainty about whether the underlying mechanism of spin-orbit torques is Rashba effect or SHE [12, 21] especially in multilayer stacks. This motivated us to explore the spin-orbit torques and their effect on magnetic behavior and microstructure of the F/HM multilayer systems. The magneto optic Kerr effect (MOKE) has been used to measure the spin polarization in semiconductors[22, 23]. We decided to utilize focused perpendicular MOKE to

observe the changes in magnetic behavior due to current-induced spin-orbit torques[24]. Traditionally, the spin-orbit torque measured using the first and second harmonic of anomalous Hall voltage[19, 20, 25]. We complemented our MOKE results with the anomalous Hall effect (AHE) measurements. The microstructural characterization is carried out using a transmission electron microscope (TEM).

Experimental setup and results

To experimentally observe the effect of spin-orbit torques on the magnetic behavior of FM/NM thin films, we chose a Co/Pd multilayer system. We utilized microfabrication to design and develop micro electro-mechanical systems (MEMS)-based devices with Co/Pd specimens for MOKE measurement and AHE characterization. We take a thermally oxidized silicon wafer with oxide thickness of 300 nm. Then the multilayer specimen is patterned by the lift-off photolithography using image reversal process. The multilayer Ta(1nm)/[Co(0.35nm)/Pd(0.55nm)]x20 specimen is deposited via RF magnetron sputtering. The second photolithography liftoff process is then performed to pattern the device electrodes. A composition of 10nm Ta/ 100nm Au is then deposited onto the wafer via Electron Beam Evaporation. Individual devices are then gold-bonded for characterization. We carried out focused P-MOKE acquisition while applying the electric current to observe the effect of spin-orbit torques on magnetic behavior of the thin film. The electrical resistance of the specimen is measured as a function of the applied direct current while recording the corresponding P-MOKE data. The resistance measurement is carried out using Keithley 6221 current source and 2182A nanovoltmeter.

{Figure 1}

This process was carried out in the presence of air. The resistance is found to increase from $310\ \Omega$ to $380\ \Omega$ for a current density of $\sim 10^6\ \text{A/cm}^2$ to $5 \times 10^6\ \text{A/cm}^2$. But once the electric current is switched off; resistance value returned to $310\ \Omega$. This suggests that even at these high current densities grain and domain structure along with the composition did not change. We carried out a similar process in-situ a magnetic force microscope (MFM) to observe the change in domain structure but the scans at $5 \times 10^6\ \text{A/cm}^2$ could not be acquired due to electrostatic interactions between the specimen and scanning tip.

In a set of experiments when the current density was increased to $4 \times 10^6\ \text{A/cm}^2$, we found that coercivity of the thin film started to decrease, but when we removed the applied electric field it reverts back to original hysteresis curve as shown in Figure 3. We repeated the experiment with different specimens, resulting in similar behavior. Then we raised the current density to $5 \times 10^6\ \text{A/cm}^2$, and we observed almost complete demagnetization of the thin film. But once again magnetic behavior is restored when the electric field is removed. These observations clearly show that coercivity of the thin film is being reduced when an electric current is applied. We know that high current density can cause significant heating in the specimen. We raised the temperature of the specimen using a heater while measuring the resistance without high-density current. This allows us to find the rise in temperature that may cause the change in resistance equivalent to high-density electric current. We found that a temperature rise of $\sim 47\ \text{K}$ results in observed change in resistance. The curie temperature of multilayer structures has been found to be between 300°C and 400°C [26]. The thin films used in the current study has been found to lose the magnetic behavior irreversibly above 300°C [27].

This shows us that temperature rise is most likely not the reason for underlying coercivity reduction.

Discussion

Among various studies on spin-orbit torques, Jamali et al. studied the effects of current-induced spin-orbit torques in ferromagnetic nanowires with composition Ta(4nm)/Ru(20nm)/[(Co/Pd)]₂₂/Ta(4nm) with perpendicular anisotropy. The composition used is significantly closer the composition presented in this work. Using a lock-in technique and the first and second harmonics of the Hall voltage, they found that the longitudinal torque is $\sim 1.17 \times 10^{-8}$ kOe*cm²/A and the ratio of the transverse to the longitudinal torque is ~ 4.3 [20]. This was attributed to the presence of dissymmetric lattice distortions, which may result in the emergence of intrinsic spin-orbit torque [28] and strong momentum scattering at the Pd/Co interfaces contributing to the in-plane torque[29, 30]. They also proposed that all the Co/Pd interfaces might be contributing towards the spin-orbit torques. Rashba spin-orbit torque results from the inversion asymmetry at the FM and NM interface.

To characterize the microstructural effects of high-density current, interfacial stresses and dissymmetric lattice structure, we carried out an in-situ TEM experiment for the Co/Pd thin films specimen. For this experiment, we fabricated a device with the TEM hole and place it inside of a custom chip carrier and mounted it with silver paste. Silver paste not only acts as an adhesive but is essential to ground the specimen in the electron beam. The electrodes of the device were then wire-bonded to the electrical contacts on the TEM chip, and the chip was then placed in a customized electrical feedthrough TEM holder. Once the device was placed in the TEM we took an initial image with no current passing through the specimen. Upon applying small amounts of current to the specimen we noticed a small increase in the resistance of the specimen, but no

change in the topology of the specimen. Furthermore, upon removing the applied current, the resistance of the specimen returned to its initial value. We increased the current to replicate the resistance change observed during earlier in-air experiments. We found that the current density of $\sim 10^6$ A/cm² is sufficient for the resistance change, and any further increase in current density results in irreversible grain growth and reduction in width of the specimen as shown in Figure 2(c)-(d). The current density required is 5 times smaller than in air experiments. This is attributed to vacuum conditions as well as the lack of a heat sink due to TEM hole underneath the specimen. More importantly, we recorded selected area electron diffraction (SAED) pattern for the Co/Pd thin films. SAED pattern can be used to identify the presence of residual stresses as well as any structural asymmetry. From the SAED pattern recorded for the Co/Pd multilayer thin films, we can clearly observe structural asymmetry since ring patterns are not circular but elliptical as shown in Figure 2(b). We are unable to index the ring pattern observed in this work because of the diffused rings. The diffused rings suggest an extremely small grain size. We would like to specify that the TEM micrographs presented in this study show the plane of the film and not the cross-section of the multilayer structure. Further increase in current resulted in grain growth and reduction in the width of the specimen as shown in Figure 2(d).

{Figure 2}

In order to verify the effect on interfacial structure on the thin film, we recorded the in-plane SAED pattern. From the SAED pattern presented in Figure 2(b), we can confirm the presence of dissymmetric lattice distortions in the Co/Pd multilayer presented in this study. Elliptical and diffused rings in SAED pattern points towards the asymmetry. And Rashba effect in multilayer thin films may originate from the interfacial asymmetry.

The SAED pattern suggest that the Rashba effect may be the underlying behavior for spin-orbit torque in the multilayer thin films. To support our hypothesis, we decided to use anomalous Hall effect (AHE) measurement to replicate the change in coercivity observed in MOKE data. We made the Hall cross bar devices as shown in figure 3 (a). We measured the AHE for a current of 5×10^5 A/cm² and 5×10^6 A/cm² on multiple devices. The AHE measurement is shown in figure 3 (a). The AHE measurement shows an insignificant change in coercivity of the Co/Pd thin films. This behavior is contradictory to MOKE data presented earlier.

{Figure 3}

In the multilayer thin films, interfaces form the bulk of the material and AHE is a bulk transport behavior. However, the AHE measurement does not show a field like torque similar to MOKE measurement. This led us to conclude that the AHE and MOKE measurements are not probing the same phenomena. We propose that AHE measurement show the transport behavior in the bulk of the thin film while MOKE data pertains to the skin (penetration depth of 1-2 nm) of the thin film. The MOKE data clearly demonstrate a field like torque leading to reduced coercivity. But the AHE data show a relatively negligible change in coercivity of the thin film for same current density. We propose that the change in coercivity observed in MOKE data is due to the spin-orbit torque resulting from the spin-Hall effect as explained in figure 3(b). Even though both Rashba effect and SHE can induce spin-orbit torques. The field like torque observed in this study originates from the SHE in Pd layers. The SHE will create a non-equilibrium spin population at the top surface leading to field like spin-orbit torque at the layers near the surface. To support our hypothesis, we calculated the transmittance for Co and Pd layers for a 633 nm laser used in the current study. The refractive index for the Co is 2.2129 and 1.8206 for Pd. The calculated transmittance for 0.35 nm Co is 0.099 whereas transmittance for 0.55 nm of Pd is

0.077[31]. These approximate calculations assume the normal incidence and two surfaces. Based on these calculations, we can confirm that the virtual magnetic field induced by SHE makes the magnetization direction tilted out of the easy axis[32] and reduces the coercive field for the thin film specimen observed in this work.

Conclusion

In conclusion, we carried out in-situ MOKE, AHE and TEM characterization of the Co/Pd multilayer thin films. We observed reversible coercivity change in MOKE measurements when direct current is applied. The TEM data shows a dissymmetric lattice structure and presence of residual stress. But no coercivity change is observed in AHE measurement. We propose that the observed coercivity change originates from surface. The MOKE technique probes the thin top layer only while the AHE data probes the bulk transport behavior. Based on these measurements, we propose that the spin-Hall effect mediated spin-orbit torque is the underlying reason for the coercivity change. The SHE will create a non-equilibrium spin population at the top surface leading to field like spin-orbit torque at the layers near the surface as observed in MOKE measurement.

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Figure 1. (a) MEMS experimental setup for MOKE and (b) in-situ MOKE reversible coercivity change.

Figure 2. TEM micrograph of Co/Pd multilayer (a) in-situ MEMS device, (b) SAED pattern of as deposited thin films, (c) TEM micrograph of thin film with no current, (d) at $\sim 10^6$ A/cm².

Figure 3. (a) Hall bar MEMS device and anomalous Hall effect measurement on Co/Pd multilayer thin films and (b) the proposed mechanism of coercivity change due to spin Hall effect.

Figure

(a)

(b)

(a)

(b)

(c)

(d)

Figure

Hall bar (Co/Pd)

specimen

(a)

(c)