Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp927-928

PS-12-10

Modeling and evaluation of interface perpendicular magnetic anisotropy in Ta/NiFe/Pt trilayers

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Abstract

Interface perpendicular magnetic anisotropy (PMA) in Ta/NiFe/Pt trilayers was investigated by using vibrating sample magnetometry. A conventional analysis based on the so-called dead-layer model revealed the interface PMA of 0.2 erg/cm^2 for Ta/NiFe/Pt. On the other hand, possible reduction of the saturation magnetization in the model of homogeneous ultrathin NiFe layer can also explain all the observed magnetic properties without taking into account the presence of interface PMA, suggesting that the interface PMA energy density determined by the dead-layer model is its upper bound.

1. Introduction

Layered structures consisting of ferromagnetic 3d-transition metal/alloy and nonmagnetic heavy metal are currently one of the most important systems in spintronics. For example, most of the heavy metals show spin Hall effect that can excite magnetization dynamics in an adjacent ferromagnetic layer. Such magnetization dynamics are often studied via ferromagnetic resonance (FMR), in which magnetic anisotropy plays an important role. Even for in-plane magnetized layered structures with only small perpendicular magnetic anisotropy (PMA), the magnitude of PMA may be necessary to determine for better understanding of the magnetization dynamics. Furthermore, it would be required to evaluate the contribution of interface PMA for comparison with first principles calculations [1].

NiFe/Pt bilayers are the popular system in spin torque FMR measurement [2]. In fact, NiFe is believed to have only tiny magnetic anisotropy, so that it is suitable for FMR-based experiments. However, it is also known that interface PMA may appear in ultrathin NiFe-based layered structures [3,4]. In this study, we investigated interface PMA in Ta/NiFe/Pt trilayer structures with model analyses.

2. Experiment

Trilayer films were prepared on a SiO_2 substrate by using rf-magnetron sputtering with a base pressure of less than 1.0×10^{-5} Pa. Prior to the formation of the NiFe (x nm)/Pt (5 nm), a Ta buffer was deposited in order to obtain flat layered structures. The thickness of NiFe was varied from 1 nm to 5 nm, and a 82 nm thick NiFe film was also prepared as a reference sample. Magnetic measurements were performed by using a vibrating sample magnetometer. All the samples showed in-plane magnetization as shown in Fig. 1. The PMA energy density K_u was given by a simplified way as $M_sH_k/2$, where M_s and H_k are the saturation magnetization and the hard-axis (i.e., perpendicular to the plane) saturation magnetic field, respectively.

3. Results and discussion

Fig. 2 shows M_s as a function of the NiFe layer thickness t. The values of $H_k/4\pi$ for the samples with t = 1 – 5 nm are also plotted, which decrease with decreasing t and are close to each M_s. This means that the observed magnetic anisotropy can fully be interpreted as the term of the shape anisotropy, if the magnetization is homogeneous within the NiFe layer. In this homogeneous magnetization model, the interface PMA energy density K_i in the Ta/NiFe/Pt trilayers is evaluated to be nearly zero.

A conventional model frequently used to determine interface PMA in bi-layers and multilayers is the so-called dead-layer model. In Figs. 3 (a) and (b), M_st and K_ut are plotted as a function of t, as in the manner of the dead-layer model. The M_st changes linearly with t, and the intercept of x-axis (t = 0.58 nm) indicates the dead-layer thickness given in this model. The K_ut also shows linear dependence on t, and thus the K_i can be determined to be ~ 0.2 erg/cm^2, as described in Fig. 3 (b). However, the real interface is not likely to be so abrupt as assumed in the dead-layer model, so that the finite magnetization and the resulting shape magnetic anisotropy contribution remains even at the dead-layer thickness. Namely, the K_i evaluated in the dead-layer model can be over-estimated and thus it is the upper bound of

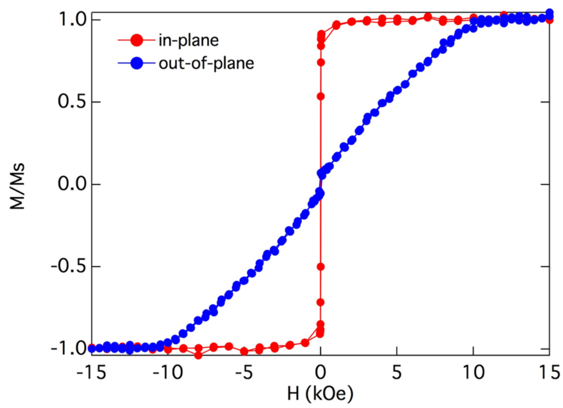

Fig. 1. In-plane and out-of-plane magnetization curves of a Ta/NiFe 5nm/Pt trilayer.

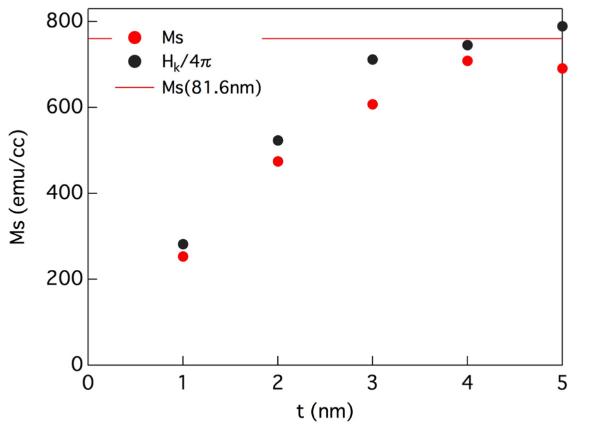

Fig. 2. Saturation magnetization M_s as a function of NiFe layer thickness t in Ta/NiFe/Pt trilayers. $H_k/4\pi$ is also plotted to compare with M_s.

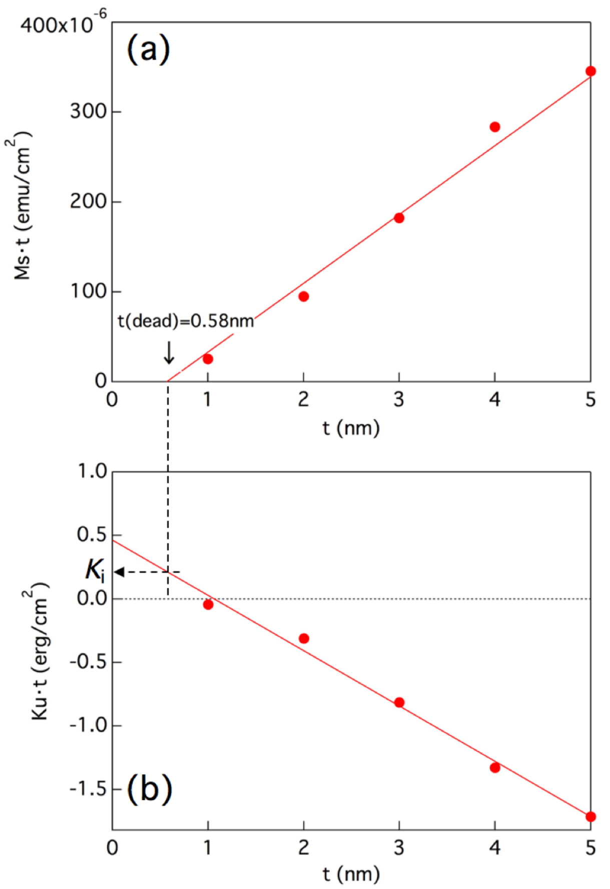

Fig. 3. (a) M_st and (b) K_ut as a function of t for Ta/NiFe/Pt trilayers. From the linear dependence in (a), the dead-layer thickness was determined to be 0.58 nm. By assuming the 0.58 nm thick dead-layer in (b), K_i is evaluated to be ~ 0.2 erg/cm^2.

interface PMA energy density.

The two models described above are considered to be the limiting cases to evaluate the K_i, and the correct K_i for Ta/NiFe/Pt can be between 0 and 0.2 erg/cm^2. It is noted that the observed temperature dependence of M_s (not shown) was consistent with the present interpretation. In our speculation, the dead-layer may be formed at the Ta/NiFe interface, while the interface PMA is likely to appear at the NiFe/Pt interface containing a large spin-orbit interaction at the Pt atom sites.

Finally, it may be worth pointing out the fact that the magnitude of the effective magnetization needed in NiFe-based FMR experiments, which corresponds to the sum of the PMA and the shape magnetic anisotropy, can be much smaller than the bulk saturation magnetization in the NiFe thickness range of < 2nm.

4. Conclusions

We investigated interface PMA in the Ta/NiFe/Pt tri-layer based on the dead-layer model and the homogeneous magnetization model. These are considered to be the two limiting cases, and the K_i has been evaluated to be in-between, i.e., 0 – 0.2 erg/cm^2.

Acknowledgment

The authors thank H. Sukegawa and M. Hayashi for valuable discussion. This work was partly supported by JSPS KAKENHI 16H02100.

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