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Magnetization reversal of antiferromagnetically coupled perpendicular anisotropy films driven by current

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ABSTRACT

By inserting an ultrathin Pt layer at Co/Ru interface, we established antiferromagnetic coupling with out-of-plane magnetization in Co/Ru/Co film stacks fabricated by sputtering. To achieve configuration suitable for free layer, the magnetic properties of the stacks have been investigated by changing the thickness of Co, Ru and Pt layers using an orthogonal wedges technique. It is found that magnetic properties for upper Co layer thinner than 0.5 nm are sensitive to little change in Ru thickness. Improving continuity of upper Co layer by slightly increasing the thickness can effectively increase the squareness of minor loop. The switching magnetization of synthetic antiferromagnetic (SAF) structure is achieved by DC current under an in-plane static magnetic field of ± 500 Oe. This structure is very promising for free layer in spintronic application.

1. Introduction

Synthetic antiferromagnetic (SAF) structure is very important to magnetic-tunneling junction (MTJ) in multiple ways [1–5]. Since the SAF coupling usually reduces the net magnetization drastically, it can serve as a pinning layer without producing too much stray field [6]. As an in-plane free layer to be manipulated by current, it can be switched often by a lower critical current [1]. Commonly, ferromagnetic (FM) layers contact the Ru coupling layer directly and consist of periodic cycles of transitional metal and Pd or Pt to maintain a large enough perpendicular magnetic anisotropy (PMA) [4,7,8]. Recently it was found that an inserted layer between FM layer and Ru layer can help the FM layers keep PMA and simplify one FM stack to merely one cycle [6,9–11]. This simplification makes it possible to produce a free layer with both SAF coupling and PMA.

The SAF coupling structure is ferrimagnet when magnetizations of two FM layers are not compensated [1]. For hysteresis loop measurement, it is common to find an additional transition in demagnetization loop before saturation [7]. This additional transition is undesired for usage of pinning layer in MTJ since it reduces stability. However, for free layer, it is a promising sign that the SAF coupling is strong enough to keep the two FM layers being switched together [12]. To form an additional transition, three energy terms are involved: exchange coupling energy, anisotropy energy and Zeeman energy, and effects like interface pinning should also be considered. It is exhausted to find a configuration with desired magnetic properties by producing a bunch of samples. In this work, the magnetization process of Co/Pt/Ru/Pt/Co stacks is investigated by modifying wedge film technique and utilizing magnetic-optic Kerr effect (MOKE) [13–15]. It was found that the additional transition is sensitively affected by a periodic change in perpendicular anisotropy. Finally, we succeeded in manipulating the magnetization of optimal SAF structure by current.

2. Experiment

DC sputtering with base vacuum better than 2×10^{-7} Torr was used to deposit our film stacks onto 15 mm × 15 mm oxidized Si substrates. In a sputtering equipment with planetary sample holders, it is common to utilize the center axis driven by a step motor and a shelter with edges perpendicular to the tangential direction of rotating. Upon this basis, another shelter with edges that rotate 45° from the tangential direction was added (Fig. 1(a)). By depositing the same material twice utilizing each opposite edge, two 45° wedges could be combined into one with gradient perpendicular to that made by the previous shelter. To eliminate influence induced by the rotating movement, the track of samples was calculated and modification was made to the nominal values of thickness.

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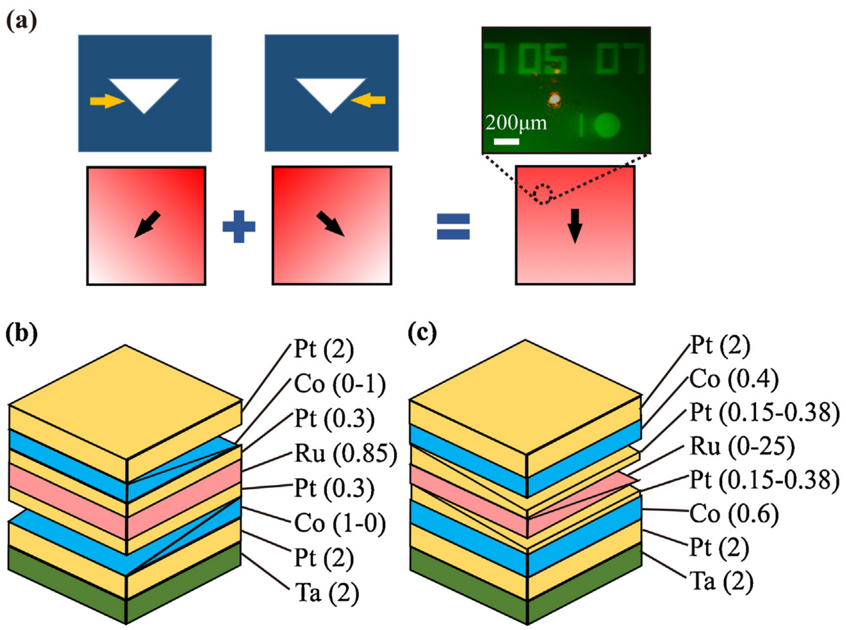

Fig. 1. (a) Diagram for making wedge perpendicular to the tangential direction of rotating, white triangle is a hole on the shelter, yellow arrows show movements of samples, the photograph shows sample after patterning and laser spot for MOKE measurement; (b) and (c) sample configurations for sample A and sample B (unit in nm), respectively. Notice the directions of the wedged layers.

Three samples were designed. All the samples have stack sequence of oxidized Si/Ta(2 nm)/Pt(2 nm)/Co(t_1)/Pt(t_{Pt})/Ru(t_{Ru})/Pt(t_{Pt})/Co(t_2)/Pt(2 nm). As shown in Fig. 1(a), for sample A $t_{Pt} = 0.3$ nm, $t_{Ru} = 0.85$ nm, and two complement Co wedges were deposited to keep $t_1 + t_2 = 1$ nm. We define $R = (t_1 - t_2)/(t_1 + t_2)$ to describe the thickness ratio of FM layers. In sample B, R was fixed to 0.2, while inserted Pt layers and Ru layer were orthogonal wedges with thickness of 0.15 nm to 0.38 nm and 0–2.5 nm, respectively. Sample C has the same configuration as sample B except for R values changing from 0.2 to 0.1. By lithography and Ar-ion etching, the samples were patterned into arrays of 150 μm plates and 20 μm wide Hall bar shown in Fig. 1(a) as a guide for measuring. Magnetization loops were obtained by a home-made MOKE system. For transport measurement, an operational-amplifier was used for combining DC driving current and AC measuring current. The Hall resistance (R_H) was obtained under a Stanford SR830 lock-in amplifier.

3. Results and discussion

Three hysteresis loops of sample A around $R = 0$ are shown in Fig. 2(a), in which good squareness can be observed in all three loops. The additional transition of $R = 0.047$ implies that the upper FM layer is the one reversing when the applied field decreases to 0, because the depth sensitive nature of MOKE makes the signal come from upper FM layer larger than the lower one. When $|R|$ is small, the switching is unnatural. When R decreases to -0.1, the magnetic behavior of two FM layers reverses corresponding to the change in net magnetization. The absence of additional transition at $R = -0.027$ indicates that the magnetization of two FM layers are consistent with nominal thickness, implying the same thickness for dead layer. To describe magnetic properties briefly, as shown in major and minor loops at $R = 0.27$ in Fig. 2(b), we define H_{ex}, H_{add} to describe strength of SAF coupling, and coercivity of additional transition. To estimate the squareness of the minor loop, the slope k was calculated by connecting middle points at 40% and 60% height of the minor loop, and an index $S = 4 + \lg(k)$ was defined to represent the squareness. It is seen from Fig. 2(c) that H_{ex} reaches a minimum around $R = 0$ and increases linearly in both directions. It is easy to understand that since SAF coupling originates from an interface effect, a thicker FM layer makes the H_{ex} lower. The squareness index S shows an opposite trend compared to H_{ex}, and it is obviously asymmetric according to $R > 0$ and $R < 0$, considering that S is logarithmic. The reason of this asymmetry may originate from different roughness of two FM layers. Since Co layers in our samples are very thin, increasing roughness and decreasing Co thickness would make the film reach the percolation limit and lead to the canted loop. The upper Co layer has a larger roughness since it is not well buffered in comparison with the lower Co layer and becomes discontinuous at larger nominal thickness. It is clear from Fig. 2(d) that with decreasing net magnetization at SAF coupling state, H_{add} enhances similarly in both directions, which means that the additional transition is mainly governed by uncompensated magnetization.

To investigate the effect of changing t_{Pt} and t_{Ru}, we map H_{ex} and S around areas showing SAF coupling in sample B. Configurations between the two areas have hysteresis loops with a single switching field, showing a conventional oscillatory coupling behavior [16]. H_{ex} decays with increasing t_{Pt}, while at each certain t_{Pt}, value, H_{ex} reaches maxima at $t_{Ru} = 0.63$ nm and 1.71 nm, implying that the inserted Pt layers simply weaken the interlayer coupling. Additional transition appears at H_{ex} as low as 360 Oe, which is smaller than the anisotropy field of a PMA film. In Fig. 1(b), both areas show the decreasing trend of S value from upper right corner to lower left corner. Weakened magnetic proximity effect with thinner Pt layers can explain decay along y axis. Along x axis, the area at right side is of higher average S. Notably the decreases of S over 0.5 nm for both areas are not monotonic. It is speculated that a periodic change in roughness caused by Ru layer is the main reason. The sample C with a slightly thicker Co upper layer that should have better continuity is measured and S mapping for $t_{Ru} = 1.6$-2.1 nm area is shown in Fig. 3(c). As our supposition, the S values at the left side are much improved. This enhancement eliminates the canted part in SAF coupling states as shown in Fig. 3(d). On the other hand, the area that allows an additional transition to occur shrinks compared to sample B, indicating that enhanced continu-