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Zigzag domain wall mediated reversal in antiferromagnetically coupled layers

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The Ruderman-Kittel-Kasuya-Yosida (RKKY) coupling between two magnetic layers leads to many important technological applications. Here, the interaction between changing antiferromagnetic RKKY coupling and domain structure is studied in a sample consisting of two 5 nm thick CoFeB layers separated by a wedge of Cu up to 4 nm thick. Magnetic reversal occurs via the propagation of a zigzag domain wall front along the wedge. The modification of domain patterns created in the reversal of a coupled layers in the presence of antiferromagnetic RKKY coupling and coupling gradients is demonstrated. Firstly, the coupling leads to a smaller amplitude of the zigzag wall, which is aligned perpendicular to the easy axis, followed by elongation of the walls at higher coupling strength. The antiferromagnetic RKKY coupling, while not strong enough to cause antiparallel alignment of the layers, is argued to lead to coupling between the spins in the domain walls in the two layers, lowering their energy and driving the reversal behavior of the film.

I. INTRODUCTION

Ruderman-Kittel-Kasuya-Yosida (RKKY) coupling allows two layers to be magnetically coupled to each other in a controllable way. By varying the thickness of a non-magnetic spacer the coupling can vary in both strength and sign (antiferromagnetic or ferromagnetic) [1]. The RKKY coupling between two magnetic layers is of technological importance and is currently used to create synthetic antiferromagnets for Magnetic Random Access Memory (MRAM) [2] or in hard drive read heads [3]. This coupling has also been exploited to create a path toward three-dimensional memory and logic devices [4], [5]. A sequence of coupled uniaxial [6], [7] or four-fold anisotropy layers [8] can be designed such that they can support a data bit, which can be propagated through the stack. By growing samples with a wedge of the interlayer material the change in RKKY coupling with thickness can be studied and the correct ratio between the anisotropy and the RKKY coupling strength can be determined [8], [9], [10], [11].

Zigzag domains are commonly found in magnetic systems with both uniaxial [12], [13] and four-fold anisotropy [14], [15]. For an in-plane uniaxial system a 180° domain wall separating two domains with magnetization aligned along the easy axis will be magnetically charged. In order to reduce the charge density a zigzag pattern can form which distributes the charge over a larger area of film at the expense of increasing the domain wall length. The exact form of the domain walls, the angle the walls make to the easy axis and the amplitude of the zigzag, is difficult to calculate because it depends on long-range stray field terms from the magnetic charge, which may even depend on the total film size [16]. Zigzag domains have been widely studied due to their prevalence in longitudinal magnetic tape recording media [16], [17]. In this application the zigzag domains are a source of noise as domains of opposite magnetization are not separated by a smooth boundary.

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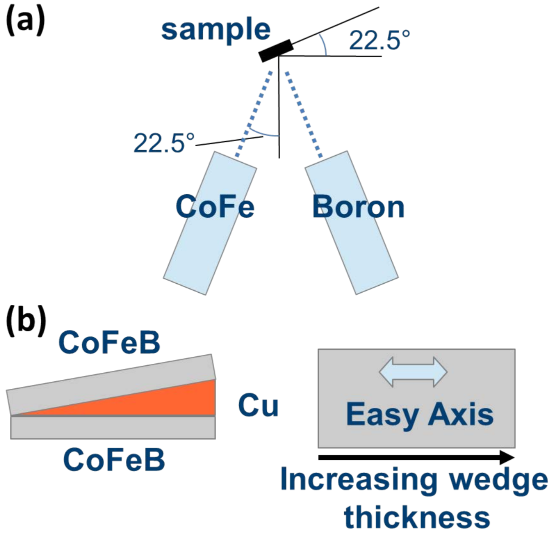

Fig. 1. (a) Schematic of the CoFeB growth geometry (b) Side-on and plan schematics of the sample studied.

In this paper we study through Kerr magnetometry the magnetic reversal of a sample where two thin in-plane magnetized layers with an induced uniaxial anisotropy are coupled together by RKKY coupling. The easy axis reversal of the film through zigzag domains is investigated by scanning Kerr microscopy which allows the effect of the RKKY coupling on the domain pattern to be elucidated.

II. SAMPLE GROWTH

The sample was grown in an MBE system with a base pressure of 4×10^{-10} mbar on a natively oxidized silicon substrate. The substrate is mounted on a tilted holder, that allows the sample to be aligned either perpendicular to or at 45 degrees to the incoming flux. Initially, a 6 nm Cu underlayer was grown with the sample normal parallel to the incoming

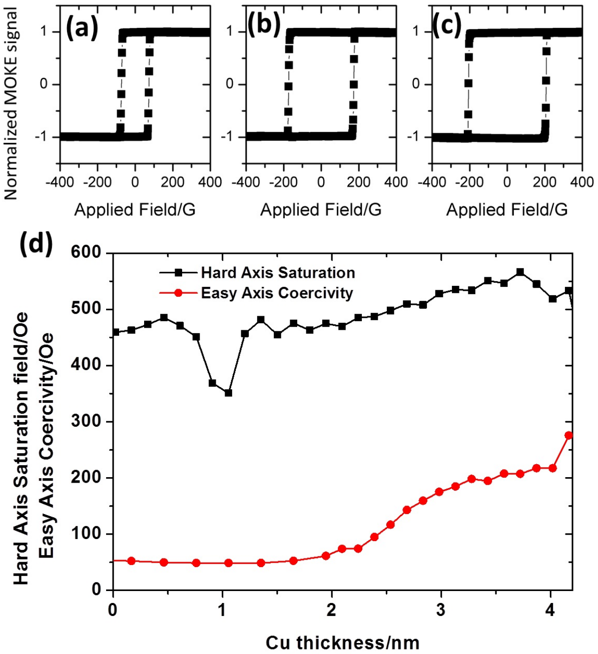

Fig. 2. (a) MOKE loop at 2.2 nm Cu interlayer thickness. (b) MOKE loop at 3.0 nm Cu interlayer thickness. (c) MOKE loop at 3.6 nm Cu interlayer thickness. (d) The easy axis coercivity and hard axis saturation as a function of the Cu interlayer thickness.

flux. The system has dual e-beam sources and the CoFeB was grown by simultaneous evaporation of $Co_{50}Fe_{50}$ and Boron as shown schematically in figure 1(a). The CoFe is evaporated at an angle of 45° to the normal of the substrate and the Boron was grown normal to the substrate. The boron content was 25 % of the final film. The boron has the effect of amorphizing the film, which, by removing the effects of polycrystalline grain boundaries leads to softer magnetic properties. The final sample geometry is shown in figure 1(b): it consists of two 5 nm thick CoFeB layers separated by a wedge of Cu created by moving a linear shutter across the sample during Cu growth. The Cu interlayer was grown with the incoming flux normal to the surface with the wedge approximately 7 mm long with a thickness from 0 nm to 4.2 nm. The sample was capped with 4.5 nm of Cr.

III. MAGNETIC MEASUREMENTS AND DISCUSSION

In figures 2(a)-(c) easy axis hysteresis loops taken at three different Cu interlayer thicknesses are shown. In figure 2(d) the coercivity as a function of interlayer thickness is given alongside the hard axis saturation field. The tilted growth provides a well-defined uniaxial anisotropy [18] of around 450 Oe in the uncoupled layer. The single sharp switches seen in the easy axis loops are at considerably lower field than the anisotropy field, suggesting domain wall mediated reversal. The hard axis saturation shows a notable dip around 1 nm interlayer thickness. This is may indicate where the two CoFeB layers become magnetically separate from each other, however, no change is seen in the coercivity. On increasing the Cu thickness to 2 nm, both coercivity and saturation remain constant, following which both the coercivity and hard axis saturation rise smoothly before the rise in coercivity stops and the hard axis saturation falls at the thickest interlayer values. The rising hard axis saturation is indicative of increasing RKKY coupling along the wedge. From theoretical calculations on antiferromagnetically coupled magnetic layers with uniaxial anisotropy [19], it is expected that for small but increasing values of antiferromagnetic coupling, the coercivity of the layers will reduce, the opposite of what is seen experimentally.

To understand the divergence of the experimental behaviour from that theoretically predicted, scanning Kerr microscopy images along the Cu wedge were taken. For each image the sample was firstly negatively saturated along the easy axis, following which the field was slowly ramped positively until the domain front reached a static laser spot at a defined position on the wedge. The field is then reduced to zero, the sample is rastered under the laser spot and the Kerr signal recorded used to produce the image. From the images, it is clear that the domains are static once the field is reduced to zero. Figure 3(a) is taken before the start of the Cu wedge and shows large zigzag and diamond structures. These are typical of thin layers with relatively large uniaxial anisotropy. The non-uniform reversal suggests there are multiple nucleation sites for the reversed domains, which may be due to the roughness of the sample.

Above 2 nm Cu thickness, where the coercivity and saturation field start increasing, a second, much smaller, length scale of zigzag domains appears on top of the larger zigzag domains (figure 3(b)). This becomes a very regular front of small zigzag domains slightly further along the wedge as shown in figure 3(c). The domains then slightly elongate (figure 3(d)), before becoming much more elongated and ragged at the higher interlayer thickness (figure 3(e)) [11]. The uniaxial anisotropy drives the initial larger zigzag domain wall formation, by

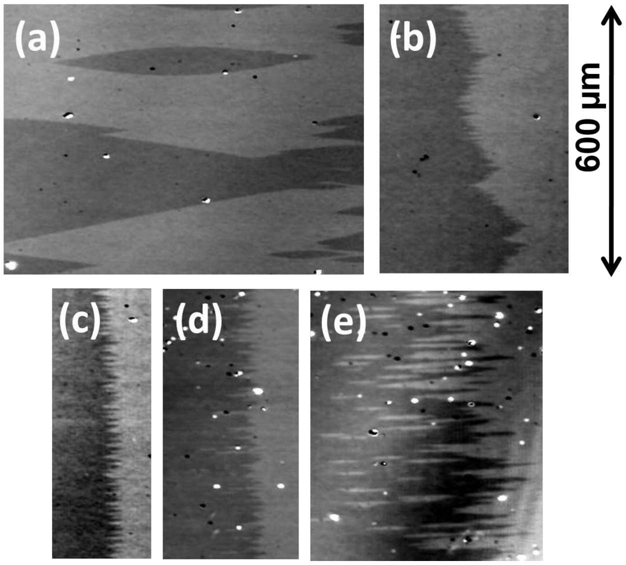

Fig. 3. Remanent field scanning Kerr microscopy images at Cu interlayers thickness of (a) 0 nm, (b) 2.1 nm, (c) 2.2 nm, (d) 3.0 nm, (e) 3.6 nm. All images are to the same scale.

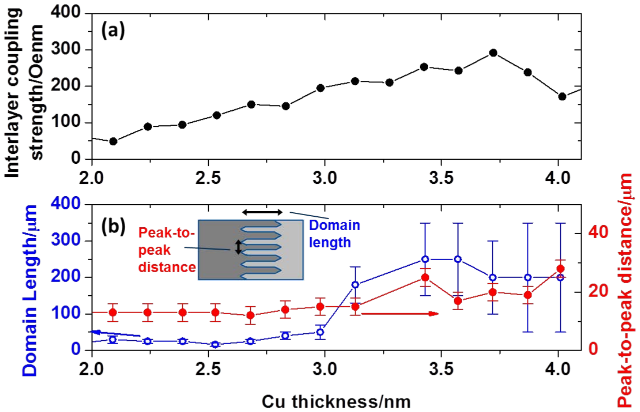

Fig. 4. (a) Derived interlayer coupling strength as a function of Cu interlayer thickness. (b) The length and peak-to-peak distance of zigzag domains as a function of Cu thickness. The error bars give the standard deviation.

making it unfavourable to rotate the spins towards the hard axis. Zigzag domains allow the magnetic charge formed at the interface of the two domains to be reduced at the expense of lengthening the domain wall [13].

The introduction of the second energy scale, that of the RKKY coupling, leads to the changes in the domain pattern [11], [20]. The extracted interlayer coupling is given in figure 4(a). This is calculated from the hard axis saturation and assumes that the intrinsic hard axis is given by the saturation field at the start of the wedge. The tilted growth tends to produce rougher films than normal incidence evaporation [18], which has the effect of smoothing out the RKKY oscillations seen for less rough interfaces [21], [22], and reducing strongly the peak coupling value that can be obtained. Here, a maximum value of just under -300 Oe nm, corresponding to -0.04 erg/cm^2 is found. The roughness of the samples probably means that the film is only coupled in patches on the microscopic scale, however, this can still lead to a measurable net coupling strength on the relatively large length scales measured here [23]. Given the ratio of the antiferromagnetic coupling and the anisotropy, it is not theoretically expected that this sample show multiple step transitions in an easy axis loop, in agreement with the experimental observation [19].

The two notable changes in the domain pattern with the onset of the RKKY coupling (see figure 3) are the formation of a well-defined front and the significant reduction in the amplitude of the domains. This is driven by the energy gradient associated with the spatially varying RKKY coupling [20]. Greater energy is required for the wall to deviate further up the wedge leading to small amplitude zigzag domains on a well-defined line. The domain wall angle is largely given by the properties of the film, such as the anisotropy and saturation magnetization [13], [24], so a reduced amplitude would also lead to a reduced peak-to-peak distance as seen.

The extracted domain wall length measured between alternating peaks as well as the spacing between peaks as extracted from the images is shown in figure 4(b). The small zigzag domain length stays constant across the first part of the increase in interlayer coupling. Then both the average domain size but also the spread of domain size (error bars) increases with increasing Cu thickness. This may be associated with a levelling off of the increase in RKKY coupling seen in 4(a), or possibly an increased spatial variation of the coupling strength. The reduction of the energy gradient allows the domains to elongate along the wedge. The domains at the thicker Cu interlayers have a pointed head, but then an elongation that runs parallel to the easy axis. This is in contrast to the diamond shaped domains seen before the start of the Cu wedge. The domains appear to be very stochastically arranged. The turning points of the domains, where the highest magnetic energy density is found, may well be preferentially located at defects with low magnetization or low coupling where this energy can be minimized. Due to these measurements being made during the reversal of the film they demonstrate the metastable configurations of the domains rather than the ground state, however, the patterns are very reproducible and it is the coercive switching behavior that is usually important for device applications.

An interesting point to consider is that of the domain walls in the two coupled films. For the Néel domain walls which are expected to exist in these thin film samples, the magnetization rotates through the domain wall in the plane of the film. For the spins in the centre of the wall in the two layers this rotation can be in opposite directions. It has been observed that these spins can favourably dipole couple to each other antiferromagnetically, stabilizing the domain wall [12], [25]. In our case the antiferromagnetic RKKY coupling also acts to stabilize this coupled domain wall. For the thicker interlayer, where the coupling strength reaches a peak, the domain walls can be very long, because the energy density of the domain wall is lowered by the RKKY coupling and there is no gradient due to the RKKY coupling to confine the lateral extent of the domain walls.

This behavior also shows that, whilst the coupling strength can be extracted from hard axis loops, the switching of thin films can depend on the details of the sample. It is possible in this case that layers made with single interlayer widths would switch differently to layers with equivalent Cu thickness on the wedge due to the different energy costs of nucleating and propagating domains compared to the wedged sample. This is important to understand for the transferability of information gained between layers that may have nominally similar parameters but the possibility of different switching behavior.

IV. CONCLUSION

In this paper we show the link between the reversal of a RKKY coupled bilayer and the magnetic domain structure studied in a CoFeB/Cu wedge/CoFeB film by scanning Kerr microscopy. The RKKY coupling both changes the size of the zigzag domains and provides a defined energy contour in the sample along which zigzag domains align and move along with increasing field. When the gradient of the coupling decreases this allows the domains to elongate parallel to the easy axis and a more stochastic set of domains is formed.

This work shows how RKKY coupling can not only affect the macroscopic switching of films but also alter the domains by which that switching occurs, which is relevant for the design of multilayer devices intending to exploit this form of interlayer coupling.

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