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Interlayer perpendicular domain coupling between thin Fe films and garnet single-crystal underlayers

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The magnetic behavior and domain structure of Fe films grown on yttrium–iron–garnet (YIG) underlayers were studied to elucidate their interlayer coupling, as a function of the Fe layer thickness, using magnetic force microscopy (MFM) and magneto-optic Kerr effect (MOKE). The YIG layer, grown by liquid phase epitaxy on single crystal gadolinium–gallium–garnet (GGG) substrates, showed a characteristic stripe domain structure in MFM images. Fe layers with thickness values of (5, 10, and 20 nm) were separately deposited on the YIG layer using ion beam sputtering system at room temperature. MOKE measurements of Fe/YIG/GGG with different Fe thickness showed that Fe films preferred to be magnetized perpendicular to the surface when the thickness was less than 20 nm. Stripe domain structure was observed for Fe thickness of 5 and 10 nm, but not for 20 nm film. Micromagnetic simulations of these Fe/YIG bilayers show that the volume exchange stiffness term at the interface plays a dominant role, when compared with the bilinear and biquadratic coupling contributions, in determining the interlayer coupling. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1689909]

I. INTRODUCTION

The magnetic structures of most ferromagnetic metal thin films are dominated by the magnetostatic energy and shown an in-plane magnetization. Exceptions are ultra-thin films with thickness less than 1–2 nm.[1–3] However, an out of plane magnetization and a perpendicular domain structure is of both fundamental and technological interest. Such a perpendicular domain structure can also be achieved by making thin multilayers of ferromagnetic layers separated by nonmagnetic spacers[4,5] that exploit the interface anisotropy or by epitaxial growth of single crystal films with perpendicular magnetocrystalline anisotropy.[6] Yttrium–iron–garnet (YIG) is a magnetic oxide material which in thin film form shows a growth induced perpendicular anisotropy[7] and a characteristic stripe domain structure.[8] Here we describe the domain structure of ferromagnetic metal layers grown on single crystal YIG thin films and the possibility of controlling the domain structure of ferromagnetic metal layers by interlayer coupling.

II. EXPERIMENTS

Bilayers of Fe thin films and YIG underlayers were fabricated on gadolinium–gallium–garnet (GGG) single crystal substrates with different thickness of Fe films (5, 10, 20 nm). GGG substrates with the YIG layer of uniform thickness, grown by liquid phase epitaxy, were obtained commercially. The Fe films were then deposited over the YIG layer by ion beam sputtering at room temperature. The Fe/YIG/GGG samples and YIG/GGG sample were investigated using magneto-optic Kerr effect (MOKE) and magnetic force microscopy (MFM). The MOKE measurements were performed to determine both the in-plane and out-of-plane hysteresis loops. MFM imaging was carried out using a low moment tip (CoCr coated). At the same time, topographic images of the samples were measured using atomic force microscopy (AFM) on the same area scanned for MFM imaging. As a separate experiment, a hard ferromagnetic alloy film ($Fe_{14}Nd_2B$) was also deposited with varying thickness (10, 15, 20 nm) and the out-of-plane hysteresis loop measured by MOKE. To understand the domain behavior of these sets of bilayers, micromagnetic simulation using the OOMMF code was carried out for the YIG single film in two-dimension and Fe/YIG bilayers in three-dimension.[9]

III. RESULTS AND DISCUSSION

A. MFM and MOKE

In Fig. 1, both out-of-plane and in-plane hysteresis loops for Fe/YIG/GGG samples using MOKE are presented (0, 10, 20 nm of Fe). A square-shaped hysteresis loop for out-of-plane measurements was observed for Fe thickness less than 20 nm. For Fe thickness of 20 nm, the out-of-plane hysteresis loop shows linear shape, but the in-plane loop shows good square hysteresis loop. These MOKE results show that the magnetization of Fe films is perpendicular to the surface for thicknesses less than 20 nm, but when the thickness reaches 20 nm, the in-plane magnetization of the domain structure is dominant in the Fe layer. To image its surface domain structure, MFM and AFM measurements were performed on the same set of Fe/YIG/GGG samples (Fig. 2). AFM images of the samples show that the topographical roughness is smoother as the Fe thickness increases and completely covers the YIG underlayer. The pair of images in Fig. 2(a) also shows the typical stripe domain structure of YIG/GGG samples. A stripe domain structure is clear evidence for a significant out-of-plane magnetization compo-

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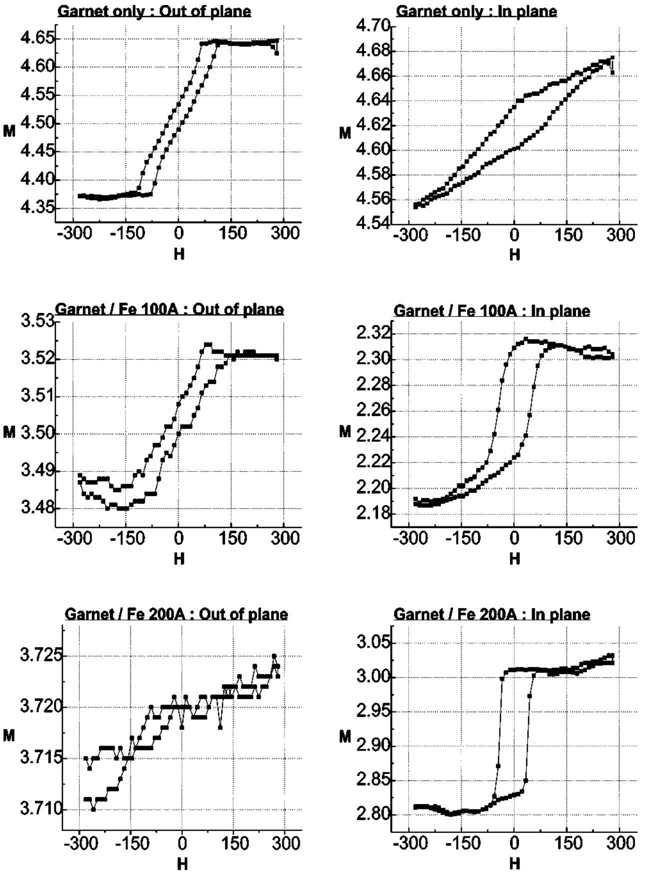

FIG. 1. MOKE hysteresis loops of out-of-plane and in-plane measurement for Fe/YIG/GGG samples (Fe: 0, 10, 20 nm).

nent. The MFM images of the samples for Fe (5 nm) and Fe (10 nm), shown in Figs. 2(b) and 2(c), respectively, also show similar stripe domains with out-of-plane magnetization components. For Fe thickness of 20 nm [Fig. 2(d)], the stripe domains are no longer observed in the MFM images, indicating that the orientation of magnetization is now parallel to the plane of the film. These results are in good agreement with the MOKE measurements (Fig. 1). In addition, the stripe domains in the Fe films (both 5 and 10 nm thick) are very similar to that of the YIG only sample in both morphology and stripe period in spite of the Fe film having very different values of saturation magnetization and magnetocrystalline anisotropy. This suggests that the domain structure of YIG film is reproduced in the Fe film due to interlayer magnetic coupling. In fact, instead of a soft ferromagnetic metal such as Fe, if we deposit a hard ferromagnetic metal layer such as $Fe_{14}Nd_2B$, the stripe domain structure remains the same. The MOKE measurement of out-of-plane and in-plane hysteresis loops for $Fe_{14}Nd_2B$ (15 nm) films deposited on identical YIG/GGG substrates are shown in Fig. 3. The out-of-plane loops for $Fe_{14}Nd_2B$/YIG/GGG shows a good square shape, but the in-plane loop shows an incomplete square-shaped loop. For 20 nm thickness of $Fe_{14}Nd_2B$, the out-of-plane loop shows a linear shape loop. This suggests that the domain structure of $Fe_{14}Nd_2B$/YIG/GGG is out-of-plane when the $Fe_{14}Nd_2B$ thickness is less than 20 nm, but the orientation of magnetization changes from perpendicular to parallel to the surface when the thickness of the $Fe_{14}Nd_2B$ layer reaches 20 nm.

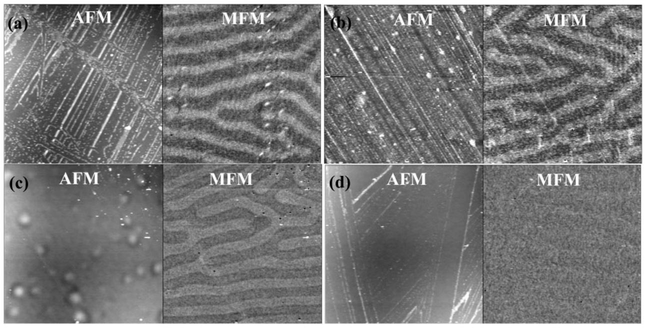

FIG. 2. AFM and MFM images of Fe/YIG/GGG samples for different Fe thickness: (a) No Fe layer, (b) Fe=5 nm, (c) Fe=10 nm, and (d) Fe=20 nm.

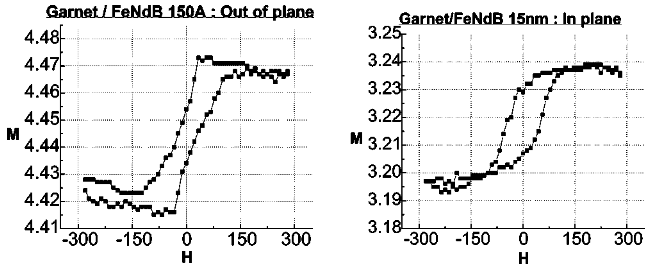

FIG. 3. Out-of-plane and in-plane hysteresis loops for $Fe_{14}Nd_2B$/YIG/GGG samples: $Fe_{14}Nd_2B = 15$ nm.

B. Micromagnetic simulation

Our experimental results indicate that the domain configuration observed in the Fe film in Fe/YIG/GGG structures arises from a strong interlayer exchange interaction between Fe and YIG layers. To elucidate the details of this interlayer coupling we carried out micromagnetic simulations of the Fe/YIG bilayers incorporating a volume stiffness energy[10] term and an interface term with both bilinear and biquadratic contributions. The volume exchange stiffness energy is expressed as[10]

$$E_{\mathrm{ex}} = A \int (\mathrm{grad} \cdot m)^2 dV,$$

where $A_{\mathrm{interface}}$, the exchange stiffness constant (J/m) at the interface, is a variable parameter in the micromagnetic simulation. The interface contribution to the energy density between two thin films can be expressed as[11,12]

$$E_{\mathrm{coupl}} = C_{\mathrm{bl}}(1 - m_1 \cdot m_2) + C_{\mathrm{bq}}(1 - (m_1 \cdot m_2)^2),$$

where C_{bl} and C_{bq}, the bilinear and biquadratic coupling constants, were also varied in the simulations. For Fe, bulk values[7] of the exchange coefficient (A), the magnetocrystalline anisotropy constant (K_1), and saturation magnetization (M_s), i.e., 21×10^{-12} J/m, 48×10^3 J/m^3, and 1700×10^3 A/m, were used. For the YIG layer, the following parameters taken from the literature[13] were used: $A = 3 \times 10^{-12}$ J/m, $K_1 = 1.333 \times 10^3$ J/m^3, and $M_s = 12.7 \times 10^3$ A/m. Simulations for only the YIG layer [Figs. 4(a) and 4(b)], show the characteristic stripe domain structure

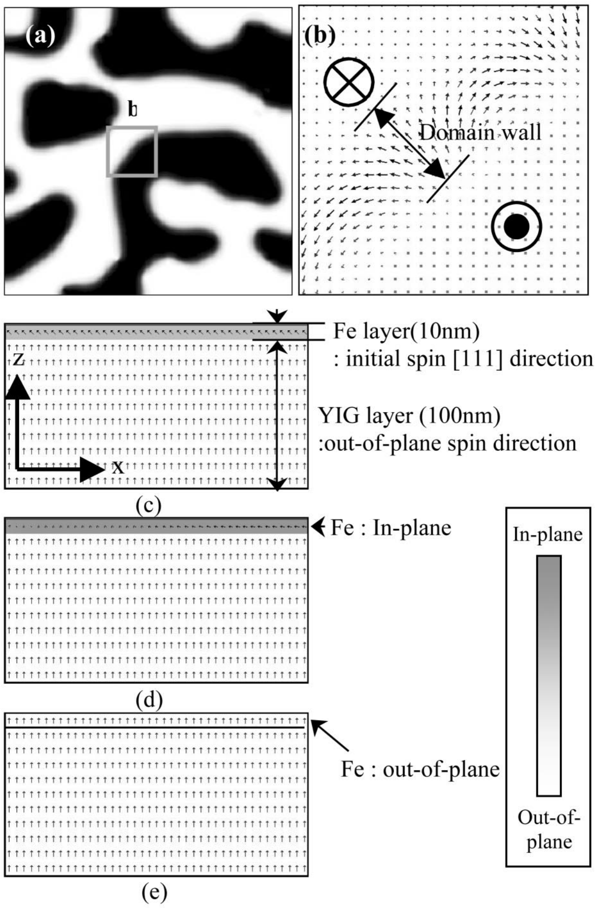

FIG. 4. Micromagnetic simulation images of YIG film: (a) domain structure of YIG film (6 μm×6 μm, xy plane), (b) domain wall image of area **b** at (a). The 3D micromagnetic simulation of Fe/YIG bilayer: (c) initial domain spin, (d) simulated domain spin when C_{bl} and C_{bq} values are varied, and (e) simulated domain spin with $A_{\mathrm{interface}} = \sim 17 \times 10^{-11}$ J/m.

with a 2 μm domain width in agreement with our experimental observations [Fig. 2(a)]. Next, the Fe/YIG bilayer domain structure was simulated using the OOMMF three dimensional (3D) solver code while varying the values of $A_{\mathrm{interface}}$, C_{bl}, and C_{bq} and keeping all other materials parameters fixed to their bulk values. The initial domain spin configuration for the Fe layer was set along the [111] direction [Fig. 4(c)]. For fixed $A_{\mathrm{interface}}$, but with the bilinear and biquadratic coupling constant varied over a wide range, the simulations always show [Fig. 4(d)] an in plane domain configuration for the Fe film. On the other hand, a strong interlayer coupling between the Fe and YIG films and a stripe domain configuration of the Fe film can be simulated [Fig. 4(e)] if the interface exchange stiffness coefficient is varied, with best results obtained for $A_{\mathrm{interface}} \sim 17 \times 10^{-11}$ J/m. The spin of YIG is perpendicular to the surface (white area), and the spin of the Fe layer is reoriented to become out of pane due to its coupling with the YIG layer. These simulations shows that the observed interlayer coupling between Fe and YIG layers can be attributed to a strong volume exchange stiffness energy contribution.

IV. CONCLUSIONS

MOKE measurement shows strong out-of-plane magnetization for both Fe/YIG/GGG and $Fe_{14}Nd_2B$/YIG/GGG samples when the thickness of ferromagnetic metal layer is less than 20 nm. MFM images, in agreement with these MOKE measurements, also show a stripe domain structure. However, the period of the stripe domains in Fe was identical to that of the pure YIG film. These experimental results suggest that this Fe/YIG bilayer system shows a strong interlayer coupling. Micromagnetic simulations using the OOMMF code reproduce these observations especially when the volume exchange stiffness term dominates. The interface bilinear and biquadratic coupling terms have minimal contribution.

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