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# Field-Dependent Magnetic Domain Walls in Exchange-Biased GdFe/TbFe Bilayers

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Exchange biasing has been widely studied in ferromagnetic/antiferromagnetic (FM/AFM) bilayers [1] and is essential for the operation of magneto-electronic devices, such as read heads in computer hard drives. This phenomenon is characterized by a shift of the magnetic hysteresis loop by an amount known as the exchange field,  $H_E$ , after field cooling. In some systems it has been shown that the exchange coupling at the interface is antiferromagnetic and that  $H_E$  can change from positive to negative values depending on the magnitude of the cooling field [2]. Theoretical models for this behavior predict the formation of domain walls in either the FM or AFM layer [1,2]. Here we describe a system in which exchange bias is the direct result of a frozen interface domain wall, revealed by polarized neutron reflectivity (PNR), whose width depends on the cooling field.

GdFe/TbFe ferrimagnetic bilayers are ideal for studying magnetic configurations in exchange-biased bilayers [3] because their magnetic behavior mimics that of typical FM/AFM biased layers. In our sample Glass/Gd<sub>40</sub>Fe<sub>60</sub>(100 nm)/Tb<sub>12</sub>Fe<sub>88</sub>(50 nm)/Al(4.5 nm)/Al<sub>2</sub>O<sub>3</sub>(3.5 nm) grown by evaporation, both Gd<sub>40</sub>Fe<sub>60</sub> and Tb<sub>12</sub>Fe<sub>88</sub> are amorphous ferrimagnets in which the Fe and rare-earth magnetic moments are antiferromagnetically coupled. In Tb<sub>12</sub>Fe<sub>88</sub>, the iron contribution to the magnetization is dominant, and the net magnetization of the alloy points antiparallel to the terbium spins. Tb<sub>12</sub>Fe<sub>88</sub> is a soft magnetic material (i.e., it has a small coercive field) at room temperature but becomes hard upon cooling. In Gd<sub>40</sub>Fe<sub>60</sub>, the contribution from the Gd is dominant, and the net magnetization is parallel to the Gd spins. GdFe is a soft magnetic material at all temperatures.

Analogous to classic exchange-spring magnets [4], the competition among the anisotropies, interlayer exchange coupling and Zeeman energies in our GdFe/TbFe bilayer gives rise to a rich magnetic phase diagram

in which spin-twists form near the interface. PNR is ideally suited for imaging vertical domain walls in ferromagnetic and ferrimagnetic multilayers [4], as it provides a depth profile of both the sample structure and the vector magnetization. PNR measurements were performed at the NG-1 reflectometer with the neutron polarization direction and the applied field maintained parallel to the TbFe uniaxial anisotropy direction in the sample plane. Polarization efficiencies exceeded 96 %. Depth-dependent magnetic and structural properties were deduced by fitting the PNR data with a model for the scattering length density that includes the possibility for a smooth magnetic twist in either the GdFe or TbFe layer [4]. While the fits were quite sensitive to the magnetization of the entire TbFe layer as well as the GdFe magnetization close to the TbFe/GdFe interface, they were much less sensitive to GdFe moments closest to the glass substrate due to the large Gd absorption.

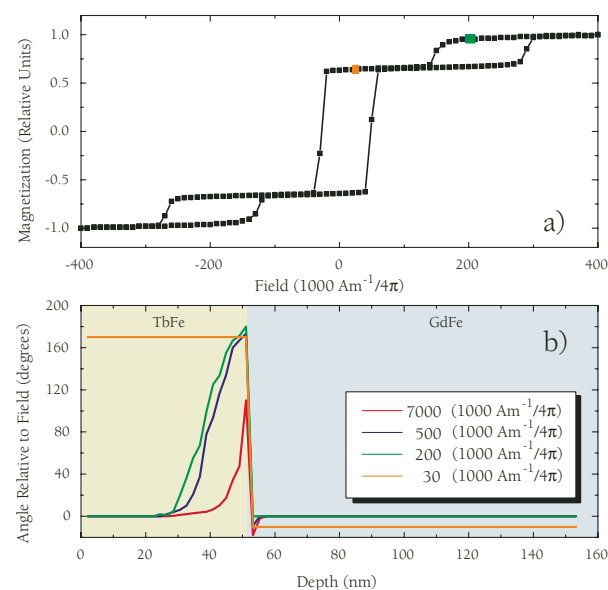


FIGURE 1: a) Magnetization as a function of field for the GdFe/TbFe bilayer at 300 K. b) Depth profile of the angle between the bilayer magnetization and the positive field direction (0°) obtained from fits to PNR data.

In Fig. 1a the magnetization is plotted as a function of field for the GdFe/TbFe sample at 300 K. Figure 1b shows the corresponding depth profile of the moment angle obtained from fits to the PNR measurements (not shown). For fields larger than  $1.19 \times 10^4$  A/m (Note:  $1000 \text{ Am}^{-1}/4\pi = 79.58 \text{ A/m} = 1 \text{ Oe}$ ), an interface domain wall (IDW) forms in the soft TbFe. In fields smaller than  $1.19 \times 10^4$  A/m, the IDW is annihilated, and the TbFe magnetization is fully reversed relative to the applied field. In general, the IDW allows for (nearly) antiparallel alignment of the GdFe and TbFe moments at the interface and for parallel alignment of the remaining GdFe and TbFe moments relative to the applied field. The thickness of the IDW decreases as the field increases.

As a next step we cooled the sample to 15 K in different fields in order to freeze the IDWs (Fig. 1b) and to probe IDW influence on the reversal of the GdFe magnetization. The field was cycled between  $1.59 \times 10^4$  A/m and  $-1.59 \times 10^4$  A/m in order to flip only the soft GdFe, and not the TbFe.  $H_E$  of the resultant hysteresis loops exhibits a pronounced dependence upon the cooling field,  $H_{cf}$ . For example,  $H_E$  increases from  $-6.4 \times 10^3$  A/m to  $7.9 \times 10^3$  A/m with  $H_{cf}$ , and  $H_E$  crosses zero at  $H_{cf} = 4.0 \times 10^4$  A/m [3].

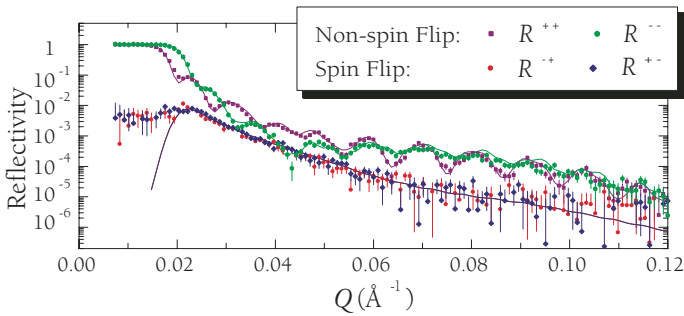


FIGURE 2: PNR spectra obtained in a field of  $1.59 \times 10^4$  A/m after cooling the GdFe/TbFe sample from 300 K to 15 K in a  $5.6 \times 10^5$  A/m field.

To best exemplify the relationship between the exchange field  $H_E$ , the cooling field  $H_{cf}$ , and the frozen TbFe spin configuration, we contrast here PNR results obtained after cooling in fields of  $5.6 \times 10^5$  A/m and  $1.59 \times 10^4$  A/m, which give rise to negative and positive bias fields ( $H_E = 4.0 \times 10^3$  A/m and  $-6.4 \times 10^3$  A/m) respectively. Figure 2 shows the PNR spectra and fit measured in  $1.59 \times 10^4$  A/m after field cooling in  $5.6 \times 10^5$  A/m. The fit indicates that a shallow IDW, with approximate thickness of 15 nm, is present in the TbFe layer (Fig. 3a). We note that the magnetic structure of the TbFe layer is frozen and nearly matches the one determined at 300 K (shown in Fig. 1b), as expected [3]. The TbFe interface moment is not parallel to its anisotropy axis, but is oriented at an energetically unfavorable angle of  $110^\circ$  relative to the positive field direction and thus gives rise to a positive biasing field. Upon reversing the GdFe magnetization in a field of  $-1.59 \times 10^4$  A/m, the small IDW in the TbFe layer vanishes and the TbFe interface moment realigns parallel to its anisotropy axis (Fig. 3a). The TbFe and GdFe moments are antiparallel at the interface (and throughout the entire layer) with the TbFe moments along the field at  $0^\circ$  and the GdFe moments opposite the field at  $180^\circ$ .

In contrast, fits to the PNR data obtained after cooling in  $H_{cf} = 1.59 \times 10^4$  A/m reveal that a larger IDW approximately 30 nm

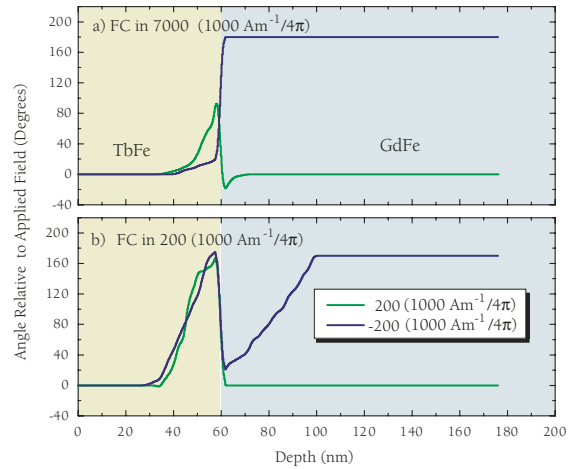


FIGURE 3: a) Depth profile of the angle between the magnetization and the positive field obtained from fits to PNR data for different applied fields after cooling in  $5.6 \times 10^5$  A/m. b) Depth profile of the angle of the magnetization after cooling in  $1.59 \times 10^4$  A/m.

thick (Fig. 3b) is frozen inside the TbFe layer and the TbFe interface moment is aligned *antiparallel* to the applied field at  $180^\circ$ . Since this TbFe configuration favors full alignment of the GdFe moment parallel to the positive field direction at  $0^\circ$ , a domain wall is forced into the GdFe layer when the field is reversed below  $H_E = -6.4 \times 10^3$  A/m. The spin structure in the reverse field involves two IDWs (Fig. 3b), and the interfacial GdFe and TbFe moments are oriented completely opposite to their directions in the  $H_{cf} = 5.6 \times 10^5$  A/m state (Fig. 3a).

Overall, the PNR measurements of TbFe/GdFe bilayers confirm that an interface domain wall, mainly located in the TbFe layer, freezes upon field cooling. PNR results also reveal that the orientation of the TbFe magnetization at the interface, as well as the thickness of the frozen IDW, is directly correlated with the magnitude and sign of  $H_E$  measured by bulk techniques. We further note that the cooling-field dependence of the TbFe interfacial angle obtained from PNR fits approximately matches theoretical predictions [5]. PNR thus provides direct access to the interface spin configuration in this biased layer and our observations of the magnetic structure in the TbFe “pinning” layer have clear implications for the nature of the frozen AFM spin state in typical AFM/FM exchange-biased systems.

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